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THE

REFRACTION AND MOTILITY OF THE EYE.

FOR STUDENTS AND PRACTITIONERS.

BY

WILLIAM NORWOOD SUTER, M.D.,

ASSISTANT SURGEON, EPISCOPAL EYE, EAR, AND THROAT HOSPITAL, WASHINGTON, D. C.

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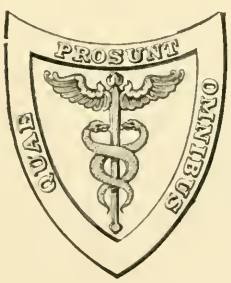

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PREFACE.

It has been the Author's endeavor to furnish a text-book on the allied subjects of the Refraction and Motility of the Eye in a manner simple enough for use by beginners in Ophthalmology, and at the same time with sufficient completeness to meet the requirements of more advanced students and of practitioners.

The mathematical formulæ dealing with the theory of refraction have been abridged to the greatest extent compatible with a proper understanding of this fundamental branch of Ophthalmology. The student who is disinclined to follow the demonstrations may learn only the conclusions reached; he may then read the other parts of the book as intelligently as if the demonstrations had been omitted from the work, as they are in most of the elementary books on refraction. The author believes, however, that every student who will master at least so much of the theory of refraction as is here given will, in his future work, be amply repaid for his trouble.

In order that the book might not be unnecessarily encumbered, specific references have not been made to the classical works of Helmholtz, Donders, and Lan-

dolt; but, for the assistance of those readers who desire a more extensive knowledge than can be given in a general text-book, the more recent authors and literature have, as far as practicable, been mentioned.

WASHINGTON, MAY, 1903.

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ABBREVIATIONS AND SIGNS.

Acc. . .	Accommodation.
Am. . . .	Ametropia (error of refraction).
As. . . .	Astigmatism.
As. h. . . .	Hyperopic astigmatism.
As. h. + As. m. .	Mixed astigmatism.
As. m. . . .	Myopic astigmatism.
Ax. . . .	Axis (cylindrical lens).
B. . . .	Base (prism).
Cyl. or C. . .	Cylindrical lens.
cm. . . .	Centimetre.
D. . . .	Dioptre.
E. or Em. . .	Emmetropia.
H. . . .	Hyperopia.
Hl. . . .	Latent hyperopia.
Hm. . . .	Manifest hyperopia.
Ht. . . .	Total hyperopia.
M. . . .	Myopia.
m. . . .	Metre.
ma. . . .	Metre-angle.
mm. . . .	Millimetre.
O. D. (R. or R. E.)	Oculus dexter (right eye).
O. S. (L. or L. E.)	Oculus sinister (left eye).
O. U. (R. and L.) .	Oculus utrique (each eye).
P. p. . . .	Punctum proximum (near-point).
P. r. . . .	Punctum remotum (far-point).
Pr. . . .	Presbyopia.
Sph. or S. . .	Spherical lens.
Str. conv. . .	Convergent strabismus.
Str. div. . .	Divergent strabismus.
Str. d. v. . .	Strabismus deorsumvergens (downward strabismus).
Str. s. v. . .	Strabismus sursumvergens (upward strabismus).
	These two expressions may conveniently be replaced by *hypertropia*, right or left, according as the right or left eye is the higher (Stevens).
V.	Vision.
+	Plus, convex lens.
—	Minus, concave lens.
⌒	Combined with (sometimes used in prescribing compound lenses).
°	Degree.
∇	Centrad.
Δ	Prism-dioptre.

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PART I.

THE THEORY OF REFRACTION.

CHAPTER I.

THE NATURE OF LIGHT.

LIGHT is that physical force which, acting upon the sentient elements of the retina, excites in the mind the impression of vision.

A substance which gives forth this kind of energy —that is, a substance which emits light—is said to be *luminous*.

Transmission of Light.—The question as to the means by which light energy is conveyed from a luminous body to the eye has given rise to two hypotheses. The first, the Corpuscular or Emission theory, was the more natural prior to the development of the science of optics. In accordance with this hypothesis it was believed that light was a substance given off from the luminous body, and that this substance was propelled in all directions in straight lines. Sir Isaac Newton was an advocate of this, in opposition to the second hypothesis (which was announced by Huygens in 1678), because in the form in which the latter was then held it failed to explain certain phenomena.

The Wave Theory.—This theory, as enunciated by Huygens and as modified by subsequent investigations, satisfactorily explains all the observed phenomena of

light; in fact, certain phenomena which follow as a necessary sequence of the wave theory were discovered through study of this theory, mathematical demonstration being afterward corroborated by actual experiment.

Ether is the extremely tenuous matter which has been assumed to exist throughout the universe, this assumption being made to explain the transmission of light.

The most familiar example of a wave is that afforded by throwing a stone into a body of still water. In this case and in sound-waves travelling in air a vibratory motion of the particles of the conductor takes place in the direction in which the wave is moving. The earlier advocates of the wave theory of light naturally supposed that in light-waves the method of vibration was similar to that of sound-waves, and since the phenomena of polarized light could not be explained under such conditions, the wave theory was abandoned for a century and a half, to be again brought into prominence by Fresnal (1815), who introduced the assumption that the vibratory motion in light-waves was transverse to the direction of wave motion—a modification, by means of which all observed phenomena of light are explainable. But this assumption cannot be accepted as excluding longitudinal vibrations, for a spherical wave can advance only in the direction in which the principal vibratory disturbance is taking place. We must conclude, therefore, that light advances by means of longitudinal disturbances upon which is superposed a transverse disturbance, and to the latter are due certain characteristic phenomena which are explainable only by means of such vibrations.

The exact nature of the vibratory disturbances which give rise to light is unknown; it was formerly supposed that there was a to-and-fro movement of the

particles of the conductor (ether), just as there is in sound-waves, but our conception of waves has been greatly broadened by the introduction by Maxwell of the electro-magnetic theory of wave conduction. In the transmission of electricity a certain unknown change (polarization) takes place in the particles of the conductor; these particles become charged with energy, which they transmit to the adjoining particles and so on. Having transmitted its energy, each particle returns to its original state and is again charged by particles behind it, and so the process continues. Since these changes occur in rhythmical impulses or pulsations, they constitute waves. Doubtless the transmission of light is similar to that of electricity; in fact, it is practically certain that light differs from electricity only in the shorter wave-length and more rapid vibration of the former.[1]

As with the ear only waves within certain limits are productive of sound, so the constitution of the eye is such that waves within certain limits of periodicity are capable of exciting vision while similar waves whose oscillatory period is not within these limits do not produce this sensation. That waves of the latter class accompany sunlight can be demonstrated with the aid of a prism, which causes a separation of waves according to their period of oscillation. It is thus shown that sunlight is composed of a series of waves differing from one another in their vibratory period.

These may be divided into three groups: (1) Those of least; (2) those of intermediate, and (3) those of greatest rapidity of vibration. These three divisions are arbitrary, but (according to the Young-Helmholtz

[1] Recent experiments in electricity lead Professor Thomson, of Cambridge, to return to the propulsion theory in a modified form. Whatever may be the nature of the corpuscles or *electrons* demonstrated by Professor Thomson, their existence is insufficient evidence for denying the theory of rhythmical impulses (waves) of electricity and light—a theory which has hitherto been found indispensable in the explanation of many phenomena.

theory) they correspond to the three sets of sensitive elements of the retina, each set being responsive to stimulation by one of the three groups of waves. The waves comprised in the first group—those of least rapidity of vibration—stimulate a certain set of retinal elements (affecting the other two sets only slightly), and this stimulation is conveyed to the brain where it gives rise to the sensation of a certain color—*red*. Similarly, stimulation of the second set of elements by the second group of waves produces another color —*green*; and stimulation by the third group produces *blue* (violet). There are thus three primary or fundamental colors, not because there are only three sets of waves, but because of the limitations of the eye; many more colors might be seen if there were more sets of retinal elements for their discrimination.

Our color-perception is not, however, limited to these three sensations, for by the simultaneous stimulation, in varying proportions, of the three sets of elements other color-sensations are afforded. When a screen is so placed as to intercept in a darkened room a beam of sunlight which has passed through a prism an observer may count on the screen six colors, clearly distinct, but each one merging gradually into the contiguous colors. These six colors are called the *colors of the spectrum*: they are red, orange, yellow, green, blue, and violet.[1] Orange and yellow, lying between red and green, result from stimulation in suitable proportions of the elements for red and green, but with little stimulation of those elements which convey violet; on the other hand, the various shades of blue result from the combined stimulation of the elements which convey green and violet with slight stimulation of the red-elements. When all three sets of elements are simultaneously and equally stimulated *whiteness* results.

[1] To these Newton added a seventh color, *indigo*, between blue and violet.

The three groups of waves which have been mentioned as composing sunlight produce the *visible* spectrum, but, as has also been mentioned, other analogous waves are transmitted from the sun along with the light-waves. The existence of waves whose period of vibration is greater than that of red-waves cannot be detected by the eye, but their presence in the solar spectrum, as heat-producing waves, can be readily determined. Similarly ultra-violet waves can be shown to accompany sunlight, but these are manifested not as heat but as chemical waves.

Thus it appears that the complete spectrum is formed by a multiplicity of waves, whose rapidity of vibration gradually increases, beginning with the ultra-red and extending through the visible spectrum to the chemical waves beyond the violet margin. In the visible part of the solar spectrum there are seen at various intervals gaps or black lines (*Fraunhofer lines*) which show that certain waves have been destroyed. The discovery of these lines has led to the important study of spectrum analysis, for it has been learned that the absence (absorption) of certain waves is characteristic of the gaseous substances through which light has passed, and that from the number and position of such lines the chemical composition of these substances can be determined.

Velocity of Light; Wave-length; Vibratory Period.—It has been found from astronomical calculations and, more recently, from terrestrial experiments, that light travels through air and through space at the rate of 300,000,000 metres (186,000 miles) a second.

The wave-length at various parts of the spectrum has also been determined by very delicate experiments. This, for red light, near the beginning of the visible spectrum, is about $\frac{1}{1300}$ mm., and for violet, near the terminus, the wave-length is about $\frac{1}{2500}$ mm. Hence,

the wave-length for light is embraced within these limits. Since light travels through space at the rate of 300,000,000,000 mm. a second, it is apparent that for the first wave-length there must be 390 million-millions of these wave-lengths or vibrations in a second, and for the last, 750 million-millions of vibrations a second.

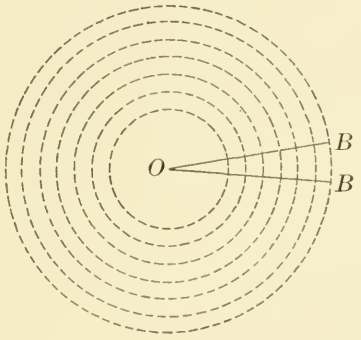
Luminosity.—By this term is denoted the intensity of the sensation which results from retinal stimulation. Yellow is the color of greatest intensity. The sensation of brightness or of *light* seems to be in a measure independent of color, for when the illumination is very feeble, one may be able to detect light and yet be unable to assign color to this light. This is always the condition in the most peripheral part of the retina. In order to explain this a fourth set of elements (for the sensation of brightness) must be assumed to exist in addition to the three color-elements assumed in the Young-Helmholtz theory of color-sensations. It has been, not without reason, supposed that the cone-elements of the retina are concerned in the distinction of colors, while the rods serve for the light-sensation.

Wave-front.—A luminous point emits light in all directions. If the rate of motion is the same in all directions, the wave-front will evidently be spherical. In any meridian, as in the plane of the paper in diagrammatic representations, the wave-front will be represented by a circle (Fig. 1).

It is a matter of common observation that light *travels in homogeneous media in straight lines*—that is, it does not bend around corners as sound does. This fact was formerly thought to be inconsistent with the wave theory, but it has been proved that the bending must diminish with the diminution of wave-length. As compared with sound-waves the length of light-waves is almost infinitesimal, and consequently the bending of light-waves must be ordinarily inappreciable; but

it can be proved experimentally that light does bend around corners to an extent commensurate with its wave-length : the shadow cast by a wire placed in the path of light is less than the actual geometrical shadow, showing that the light has to a slight extent curved

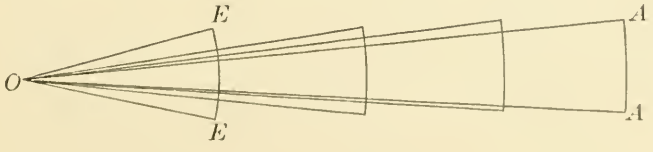
FIG. 1.



around the borders of the wire. The study of this phenomenon, called *diffraction*, constitutes an important branch of optics.

From Fig. 2 it is apparent that the nearer the eye is to the source of illumination the greater is the portion of the wave which will enter the eye. Hence, the luminosity diminishes with the increase of dis-

FIG. 2.



tance of the luminous body. It is also apparent that the curvature of the wave-front diminishes with the increase of distance. When the radius $O\,A$ is so great that the portion of the wave $A\,A$ may be regarded as a straight line, the wave is said to be *plane*.

Pencils and Rays.—That portion of a wave included by an arc is called a *pencil*. An infinitesimal pencil is called a *ray*. The lines $O\ A$ and $O\ E$ represent rays. Hence, a ray of light is represented by a straight line perpendicular to the wave-front.

Superposition of Waves.—We do not ordinarily have to deal with mere points of light, but with objects of appreciable size. Spherical waves proceed from every point of a luminous object. Hence, we must infer that many waves may traverse the same space at the same time without destroying one another. This is known as the *principle of superposition*; it has its analogue in the superposition of motions. An object acted upon simultaneously by two forces will be displaced by each force as if the other had not acted, and the resultant displacement will be the same as if the object had first been displaced by one and subsequently by the other force. Just as it is possible that these two forces might act in opposition so as to neutralize each other, so is it possible that light-waves of a certain length (color) may be destroyed by other waves of the same length acting in opposition to the first. In this way (by the destruction of certain waves) objects assume their characteristic color, although illuminated by sunlight, which contains all the colors. It is by the production of an experimental interference of light-waves that the wave-lengths for the different colors have been determined.

CHAPTER II.

REFLECTION AND REFRACTION. PRISMS.

A TRANSPARENT substance—a substance which permits the passage of light through it—is called a *medium*. When light traversing one medium meets another of different density, some of the light is transmitted to the second medium and some of it is reflected back into the first medium. If the second medium is perfectly transparent, these two portions constitute the total energy of the incident wave; but all known substances offer some resistance to light, and a certain portion of the incident wave is absorbed—converted into some other form of energy.

Many substances which, in thin layers, are transparent, offer such resistance to the passage of light that only a small part of an incident wave can pass through thick strata of these substances. On the other hand, a substance which under ordinary circumstances appears to be opaque, may be seen to be not entirely so when placed in the path of light of great intensity.

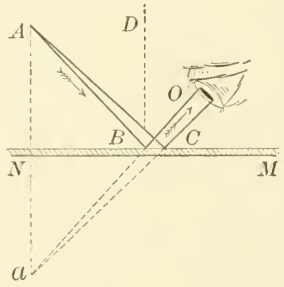
The difference between a transparent and an opaque body lies in the structural peculiarity of the substance. A common illustration of this difference is that afforded by ice or glass, both of which are transparent in (thin) homogeneous layers, but opaque in a crushed or pulverized condition. The opacity in the latter state is due to the intermixture of air between the particles of denser material; the wave being broken up by reflections at each of the many surfaces, its penetrating power is soon lost. Some of this reflected light finds its way back to the medium from which it came, while

the remainder by to-and-fro reflections, sets up disturbances in the opaque body, producing, usually, heat-vibrations.

If no light were reflected to the eye from an object, the latter would be invisible, or if surrounded by light-reflecting objects, it would appear black, but without structural detail; but under good illumination some light is reflected from almost all objects. When this is very slight and with no one color predominating the object appears gray or black, according to the quantity of light reflected. In many objects light of a certain color is abundantly reflected, while that of other colors is absorbed. The color which is predominantly reflected is the characteristic color of the object.

The Law of Reflection.—This is illustrated in Fig. 3; a ray of light, *A B*, meets a surface, *M N*,

FIG. 3.



Illustrating the law of reflection. (From Ganot.)

and the ray is reflected from the surface in such manner that the angle of incidence, *A B D*, is equal to the angle of reflection, *D B O*, both angles lying in a common plane. Similarly, every other ray of a pencil, *B A C*, is so reflected. When the surface is plane and smooth, as in the figure, all the normals are parallel, and the reflected pencil will appear to proceed from a point, *a*, which lies as far behind the surface as *A* lies in front of it. When the surface is

regularly curved the point, a, of intersection of any two rays can be ascertained from the geometrical construction and the law of reflection, but it will be found that for spherical curvatures it is only when we isolate small pencils that we may regard all the rays of the pencil as coming from a single point. In reflection from smooth surfaces, such as described, one sees only an image of the illuminating object; the surface itself is invisible. This is called *regular* reflection.

When the reflecting surface is uneven it is apparent that the reflected wave will have no regularity of form. Light reflected in this way is said to be *irregularly* reflected or *scattered*. It is by means of such scattered or diffused light that we see objects which are not self-luminous. Light reaches the surface of an object by reflection from surrounding objects, and is again reflected in all directions by the uneven surface. Some of the rays from each point of the object reach the eye of an observer, forming a small pencil whose centre is at the point specified; this pencil and similar pencils from other parts of the object being properly focused on the retina, the object is rendered visible. Many surfaces are so smooth as to reflect an image of the illuminating object, and at the same time sufficiently uneven to be visible by irregular reflection. Thus it is possible to see in a mirror an image of a flame, apparently behind the mirror, and at the same time to see the surface of the mirror by irregular reflection, although when a mirror is very highly polished its presence may readily escape visual detection. The fundus of the eye is of this character, but in this case the proportion of irregularly reflected light is much greater, allowing the fundus to become distinctly visible, while the somewhat faint image of the illuminating source is disregarded.

The Law of Refraction.—When light passes from one medium to another of different density the form of

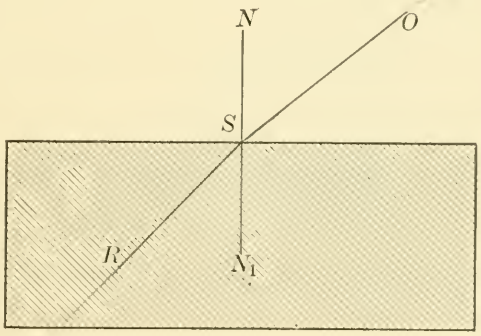
the wave-front is altered, and consequently the directions of the various rays (which are always perpendicular to the wave-front) are also altered. By this change the course of the rays is broken or *refracted*. Hence, refraction is the change of direction which rays of light undergo in passing from one medium to another. The law of refraction was discovered by Willebrod Snellius (1621), Professor of Mathematics at Leyden. This law has been expressed by Descartes in the following terms: *The incident and refracted rays are in the same plane with the normal to the surface; they lie on opposite sides of it, and the sine of the angle of incidence always bears a constant ratio to the sine of the angle of refraction.* Denoting the angles of incidence and refraction by i and r respectively, this relation is expressed by the equation sin i=n sin r. The constant ratio n is called the *refractive index* for the two media.

Snell deduced this relation by recording the results of many experiments. He knew nothing of the wave theory of light, of which the law of refraction is a necessary sequence, the constant n representing the relative velocity of light in the two media. If v and v_1 represent the velocity in the first and second medium, respectively, $n=\frac{v}{v_1}$. If the first medium is a vacuum (ether), whose velocity is represented by unity, the refractive index is $\frac{1}{v}$. This is the *absolute* refractive index. The absolute index of air (1.0003), being so nearly unity, is regarded as such in our calculations. If the absolute indices of two media are denoted by n and n_1 respectively, the relative index for the two media will be $\frac{n_1}{n}$, and the law of refraction will be expressed by the equation $n \sin i = n_1 \sin r$.

Since the sine of an angle increases with the angle, it appears that when n_1 is greater than n (when light

passes from a rarer to a denser medium) the angle of incidence ($N\ S\ O$, Fig. 4) is greater than the angle of refraction ($N_1\ S\ R$); when n_1 is less than n the angle of refraction is greater than the angle of incidence. Hence, when light passes from a rarer to a denser medium the rays are bent *toward* the normal to the surface at the point of meeting, and when light passes from a denser to a rarer medium they are bent *away* from this normal. It also follows from the foregoing equation that the deviation (refraction) of a ray increases with the angle of incidence, since the sine of an angle increases less rapidly than the angle, and the more so

FIG. 4.

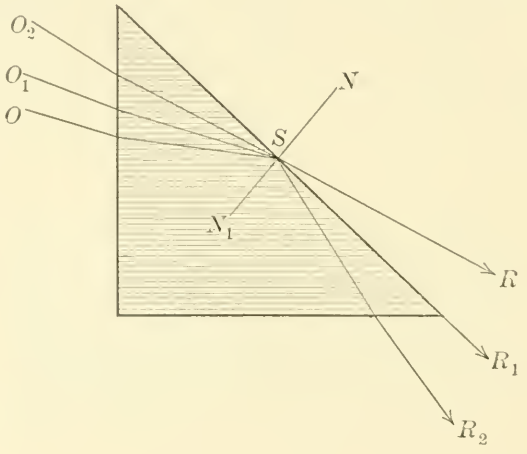


according as the angle is greater. Hence, in order to maintain the constant ratio n, the greater angle (whether this is the angle of incidence or of refraction) must increase more rapidly than the smaller angle, and, consequently, the deviation increases with increase of the angle of incidence. When the angle of incidence is zero the angle of refraction is also zero—that is, the ray which meets a surface perpendicularly undergoes no refraction.

Total Reflection; Critical Angle.—When light traversing a rare medium arrives at a denser medium, a portion of this light always enters the second medium,

although this portion diminishes while the reflected portion increases with increase of the incident angle; but when light passing through a dense medium meets a rarer one, none of the light passes into the second medium when the incident angle is increased beyond a certain limit. This is illustrated in Fig. 5, in which the triangular figure represents a section of a dense medium. A ray of light, $O\ S\ R$, passes through this medium, leaving it at S; $N\ S\ R$ is the angle of refraction, the ray being bent away from the

FIG. 5.

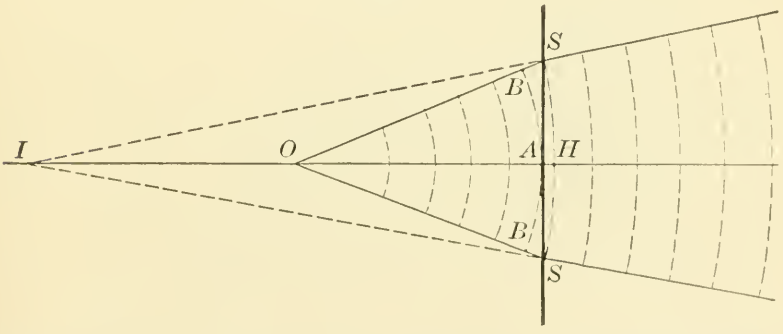


normal on emergence from the dense medium. As the angle of incidence is increased the angle of refraction must also be increased, and the latter being larger than the angle of incidence, it must be increased more rapidly than the angle of incidence. Hence, it is apparent that when the incident angle is increased to a certain extent, the refractive angle will become 90°, and the ray $O_1\ S\ R_1$ will travel along the bounding surface. The incident angle which produces this result is called the *critical angle*. If the incident angle is still further increased, as in the ray $O_2\ S\ R_2$, it is apparent that none of the light can pass out of the

dense medium at *S;* this condition is called *total internal reflection.* The critical angle varies with the refractive index; if this is known, the critical angle can be ascertained by making the refractive angle *r* equal to 90° in the equation sin i=n sin r. On the other hand, this principle affords a valuable method of determining the refractive index of any dense substance. The incident angle at which light ceases to pass out of a dense substance can be measured; this must correspond to a refractive angle of 90°, and, knowing both *i* and *r* in the foregoing equation, the index *n* can be determined.

Refraction of a Spherical Wave at a Plane Surface.—In Fig. 6, *S O S* represents a section of a

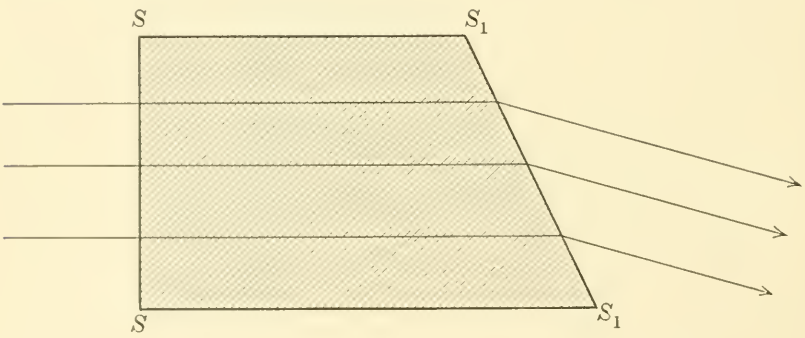
FIG. 6.



spherical pencil of light which enters a dense substance at the plane surface *S S*. That part of the wave which travels along *O A* meets the surface sooner than that which travels along *O S;* while the latter is travelling the distance *B S*, the ray *O A* advances to *H* in the dense substance. It has been proved experimentally that the progress of light is impeded by dense matter, and the more so as the density is greater; hence, the distance *A H* is less than *B S*. Similarly, the progress of the various portions of the wave between *O H* and *O S* is impeded as these portions reach the dense sub-

stance, and when the peripheral portion $O\ S$ has reached this substance, the wave-front will be represented by the arc $S\ H\ S$—that is, the wave has become flattened, and if this line is the arc of a circle, its centre lies not at O, but at some point, I, farther from the surface than O. In reality, this line, $S\ H\ S$, is not strictly circular, but for small pencils of light it differs so slightly from a circle that it may be regarded as such. With this understanding we say that a pencil of light proceeding from a point, O, and entering a medium of greater density at a plane surface, $S\ S$, will proceed in this dense medium as if diverging from a point, I, farther from the surface than O. Since

FIG. 7.

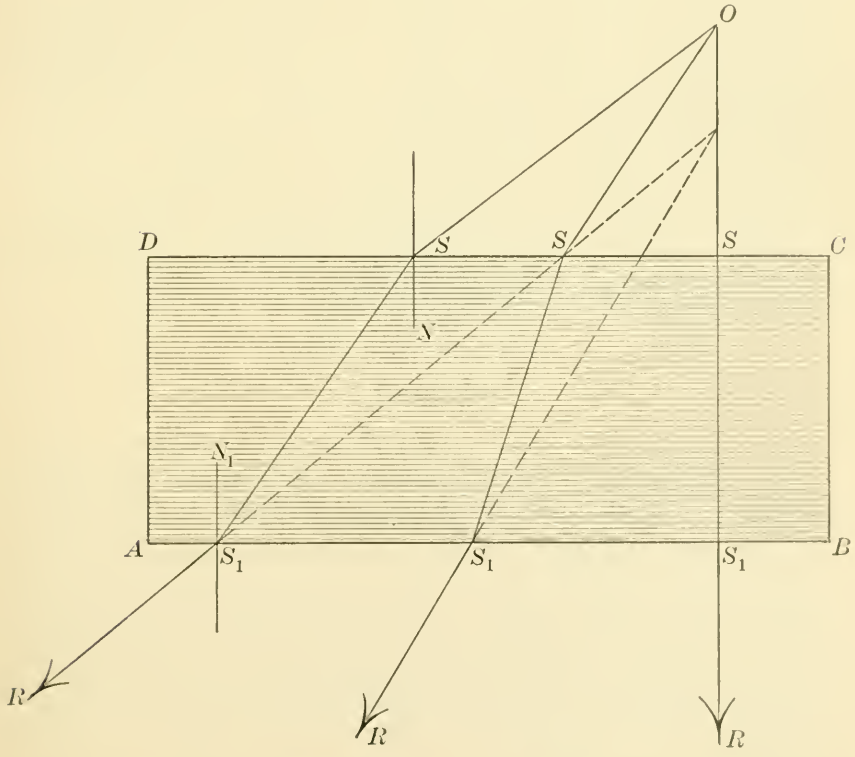


light appears to advance in the direction of its rays, at right angles to the wave-front, it is clear that the ray $O\ A$ undergoes no refraction, while any other ray, as $O\ S$, is refracted so as to appear as the ray $I\ S\ R$—that is, as we have already learned, the rays are refracted *toward* the normal to the surface.

If, on the other hand, light passes from a denser to a rarer medium at a plane surface, the effect upon the wave-front is opposite to that just described—that is, in this case the divergence of the pencil is increased, whereas in the passage of light from a rare to a dense medium the divergence is diminished.

Passage of a Plane Wave from One Medium to Another at a Plane Surface.—If the point O is so far distant that the wave may be regarded as plane, all the rays being perpendicular to the surface, there will be no refraction of any of these rays as at the surface $S\ S$ (Fig. 7). If a plane wave strikes a plane surface obliquely, all the rays will be equally refracted; the direction of the wave will be altered, but the parallelism of the rays will not be affected, as at the surface $S_1\ S_1$ (Fig. 7).

FIG. 8.



Passage of Light through a Medium Bounded by Two Plane and Parallel Surfaces.—In Fig. 8, $O\ S\ S_1\ R$ represents any ray of a pencil passing through the medium $A\ B\ C\ D$; the ray emerges from the

second medium at S_1 and passes into the surrounding medium, this being the same as that in which the pencil was travelling prior to entrance into the second medium. Since the two surfaces are parallel, the normals at S and S_1 must also be parallel; hence, the angle of refraction $N\,S\,S_1$ must be equal to the angle of incidence $N_1\,S_1\,S$, and consequently the angle of refraction at the second surface must be equal to the angle of incidence at the first surface—that is, the deviations at the two surfaces exactly neutralize each other, and the direction of the ray after emergence is parallel to that before entrance into the second medium. Hence, in passing through a medium bounded by parallel plane surfaces all rays maintain their original direction, but all oblique rays undergo a lateral displacement which varies with the thickness of the medium. Hence, the divergence, parallelism, or convergence of a wave will not be altered by this means, but the point of origin will be shifted in accordance with the thickness of the medium.

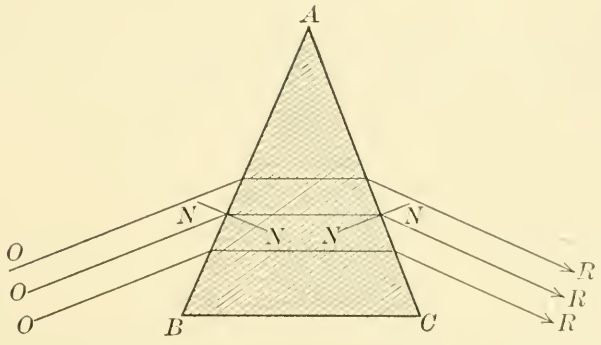
PRISMS.

A prism is a wedge-shaped portion of material bounded by two plane surfaces meeting in an edge. The angle included by these two faces is called (in optics) the *refracting angle*. A plane which is perpendicular to the edge, and consequently to each face of the prism, is called a *principal plane* of the prism. At right angles to any principal plane—that is, in the direction of the edge of the prism—the two faces are parallel to each other.

Refraction of Rays by a Prism.—A ray of light passing through a prism whose refractive index is greater than that of the surrounding medium will always be deviated *away* from the apex or edge of the

prism. In Fig. 9, *B A C* represents a principal section of a prism whose refracting angle is *A*; *O R* represents a series of parallel rays lying in a principal plane of the prism; at the first surface the rays are bent toward the normal to this surface and at the second they are bent away from the normal; the effect in both instances, as illustrated, being to deviate them away from the apex of the prism. This, however, is not always the case; the rays may strike the first surface perpendicularly, or they may emerge from the

FIG. 9.

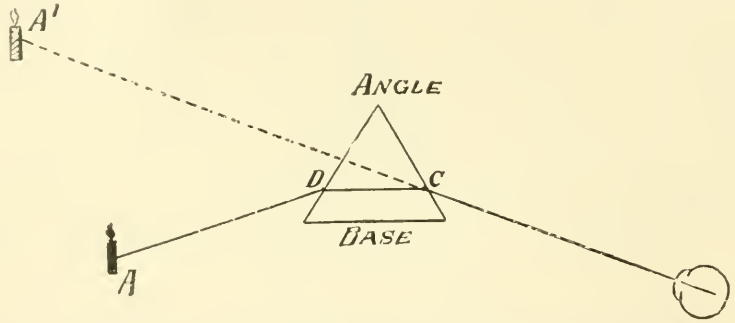


second surface perpendicularly, or they may even be bent toward the apex at one or the other surface. In this last case it is necessary to prove that the bending toward the apex is less than the opposite bending at the other face of the prism. This is easily done by geometrical construction, from which it appears that the angles of refraction and incidence are greater at that surface at which the rays are bent away from the apex, and since the deviation increases as these angles increase, it follows that the deviation away from the apex always outweighs that toward it.

Since a prism deviates light away from its apex, the apparent position of an object as seen through a prism is displaced toward the apex (Fig. 10).

Minimum Deviation.—Sir Isaac Newton determined (and it may also be proved mathematically) that the deviation of a ray of light is less when it passes through a prism symmetrically (as in Figs. 9 and 10) than in any other position. As a prism is turned from this position the deviation increases, and at a continually increasing rate. In a prism of glass (index, 1.5) the angular deviation of the symmetrical ray is approximately equal to $\frac{1}{2}$ of the refracting angle when this is small (not more than 6° or 8°), but the deviation exceeds this for large refracting angles.

FIG. 10.



Dotted lines indicate direction which the projected beam takes. (Hansell and Reber.)

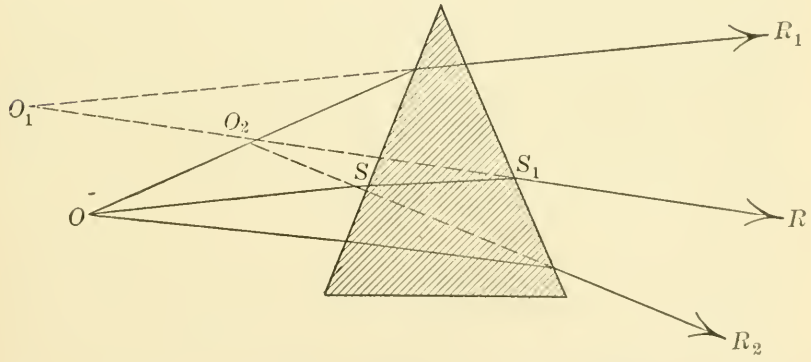
Dispersion of Colors.—Allusion has already been made to the separation of colors by prismatic refraction. This separation of colors is due to the fact that the degree of deviation by the prism varies with the wave-length, being least for red and greatest for violet. The deviation or refraction of light is caused, as we have learned, by the retardation which it undergoes in its passage through dense media, and, accordingly, it must be assumed that the degree of retardation increases as the wave-length diminishes. This unequal velocity is the result of disturbance of the wave motion; through space and through air the many component waves travel with equal velocity.

In order to obtain a spectrum it is necessary to exclude all light except a narrow beam, otherwise the waves which pass through various parts of the prism overlap and form the compound light, only that part of the light which passes along the borders being tinged with color.

Refraction of a Plane Wave by a Prism.—This is illustrated in Fig. 9; the rays all being parallel before entrance into the prism, must remain so after emergence, since the angles of incidence are the same for all the rays. Hence, the parallelism of rays is not disturbed by prismatic refraction, though the direction in which the wave travels is altered.

Refraction of a Spherical Wave by a Prism.—When a wave enters a prism diverging from a point,

FIG. 11.



the angles of incidence differ for the different rays of the wave. This is illustrated in Fig. 11, in which O is the point of origin of the wave, $O\ R$ is the ray of minimum deviation, $O\ R_1$ and $O\ R_2$ are other rays passing through the prism as illustrated. The ray $O\ R$ is so deviated as to appear to proceed along the line $O_1\ R$; since this is the ray of least deviation, both $O\ R_1$ and $O\ R_2$ undergo greater deviation than $O\ R$. The ray $O\ R_1$ will be so deviated as to appear to come from O_1, meeting the backward prolongation

of the ray $(O\ S)\ S_1\ R$ at O_1. Hence, if we may assume that all the rays between $O\ R$ and $O\ R_1$ appear to come from this point, O_1, the latter represents the point of origin of the refracted pencil. Since the ray $O\ R_1$ undergoes greater deviation than $O\ R$ does, it is apparent that the divergence of the pencil is diminished and the point O_1 is farther than O is from the prism. The ray $O\ R_2$ also undergoes greater deviation than $O\ R$, but in this case the effect of this is to increase the relative divergence of rays lying between R and R_2. Hence, the point O_2 from which these rays appear to diverge is nearer the prism than O. It is only when we isolate small pencils that we may regard all the rays as having a common meeting-point, for no two rays undergo exactly the same deviation. The difference in deviation is least for those rays which are near the position of the symmetrical ray. It is permissible to assume that in a weak prism a small pencil, whose axis is the ray of minimum deviation, will not be altered in length; the position of its apparent point of origin will be displaced toward the apex of the prism, but the distance of this point from the prism will not be affected. As the position of minimum deviation is more remote the change of deviation for the successive rays becomes more rapid, and even when a small pencil is isolated there is appreciable alteration in the apparent distance of the point from which the light seems to proceed. In accordance with the illustration (Fig. 11) we learn that this distance is increased or diminished according as the pencil *enters* the prism more or less obliquely than the symmetrical ray, or according as the base or the apex of the prism is turned toward the object.[1]

[1] The nearer the apparent position of an object is moved toward the eye the larger does the object appear, since the visual angle is thereby increased. Consequently prisms cause an apparent magnification or minification of objects in the principal plane according as the apex or the base of the prism is turned toward the object.

The foregoing paragraph applies to the deviation in the principal plane of the prism. At right angles to this plane the faces of the prism are parallel and in this direction there is no deviation of rays. These all have the same relative position, so far as this plane is concerned, as they had before entering the prism. Hence, the only pencil which will appear to proceed from a point after refraction is that which occupies the position of minimum deviation; other pencils are lengthened or shortened in the principal plane and unaffected in the direction of the edge of the prism; there is thus a separate focus for each of these two meridians, and the refracted pencil is astigmatic. This will be more fully explained in considering the subject of astigmatism. (See Chapter VII.)

Numeration of Prisms.—Several methods of numbering prisms are in use. The old and until recently the common method consists in designating the prism according to the refracting angle (Pr. 1°, 2°, 3°, etc.). The theoretical disadvantages of this method are obvious, although from a practical standpoint it differs from the modern methods chiefly in nomenclature, at least for the weak prisms which are commonly used in ophthalmology.

In response to a demand for a more satisfactory scale, it was proposed to number prisms in terms of the *minimum deviating power* (Pr. 1^d, 2^d, etc.). For the weaker prisms this is slightly more than one-half the refracting angle; a prism of 2^d is approximately the same as one of 4° (refracting angle system). For the stronger prisms the deviation is proportionately greater; a prism of 12° produces 6.5° of deviation.

Based upon the same principle is the *centrad* system (Dennett). In this the deviation is measured, not in degrees, but in centrads, a centrad being $\frac{1}{100}$ of the radius as measured on the circumference. The circumference of a circle being 360°, and the radius being

(approximately) $\frac{1}{6.2832}$ of the circumference, the centrad ($\frac{1}{100}$ of the radius) is found to be 34′ and 22″, a little more than $\frac{1}{2}$ of a degree.

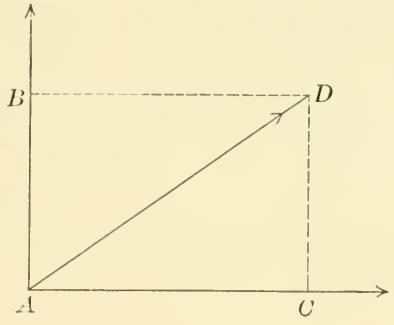
The *prism-dioptre* (Prentice) differs from the centrad only in that the former is measured as a straight line while the centrad is an arc of the circumference. A prism-dioptre is the strength of prism which deviates a ray $\frac{1}{100}$ of a metre at a distance of one metre. This method of numeration affords a very easy way of testing the strength of a prism, it being only necessary to count, on a suitable scale, the number of centimetres of displacement which a line undergoes when the prism is placed at a distance of one metre from this scale. The prism-dioptre has been adopted as the unit of measurement by the principal optical manufacturers of America, who make all their prisms in accordance with this scale. The character △ is commonly used to express this unit.

The *metre-angle*, of which mention will be made in a subsequent chapter, has also been suggested as a prism-unit. The value of this unit depends upon the interocular distance, and as this varies considerably, the metre-angle is unsuitable for numbering prisms, though very convenient in the estimation of convergence.

Combination of Prisms.—It is sometimes desirable to substitute a single equivalent prism for two prisms acting in different directions. This is readily done by diagrammatic construction, as is illustrated in Fig. 12. Suppose, for instance, we wish to find the equivalent of two prisms; the first of 3△, acting horizontally, and the second 2△, acting vertically. We proceed by measuring off 3 cm. (*A C*) in the direction of deviation of the first prism—*i. e.*, toward the apex of the prism; we next measure off 2 cm. (*A B*) in the direction of action of the second prism. The effect of the two prisms acting together will be represented by the line

A D; hence, the number of centimetres (3.6) in *A D* corresponds to the number of prism-dioptres of the equivalent prism. The direction of the base-apex line is also determined by *A D*, the base being at *A*. The angle *D A C* (in this case 35°) may be measured with a protractor.

Fig. 12.



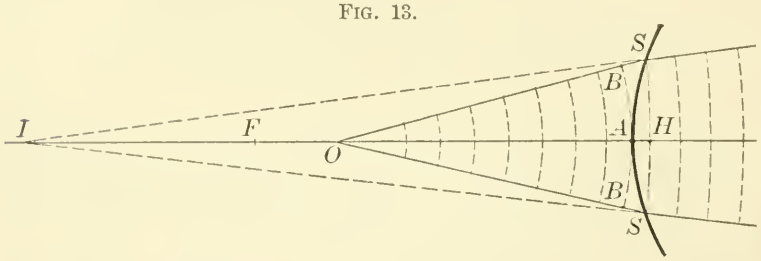
The same diagram serves for reversing this process —that is, for replacing a single prism, acting in an intermediate meridian, by two prisms, one acting horizontally and the other vertically.

CHAPTER III.

SPHERICAL REFRACTION.

When a spherical pencil of light, proceeding from a point, passes from a rarer to a denser medium at a convex surface, the central rays arrive at the second medium sooner than the peripheral portion of the wave; consequently the wave-front undergoes a diminution of curvature, as is illustrated in Fig. 13.

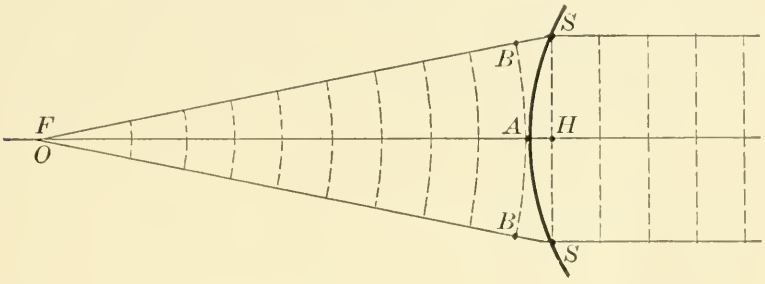
Fig. 13.



The flattening of the wave occurs in the same manner as in refraction at a plane surface (described in the preceding chapter), but, as is apparent from the diagram, the relative retardation of the central rays, and consequently the flattening of the wave, increases with the convexity of the surface. In refraction at a plane surface a wave diverging from a point, *O*, will always remain divergent, appearing to proceed from another point, *I*, the two points being on the same side of the surface. But in refraction at a convex surface, rays which before refraction diverge from a point may be rendered parallel (Fig. 14) after refraction, or they may even be rendered convergent (Fig. 15), the wave which proceeded from *O* being concentrated at the point *I*.

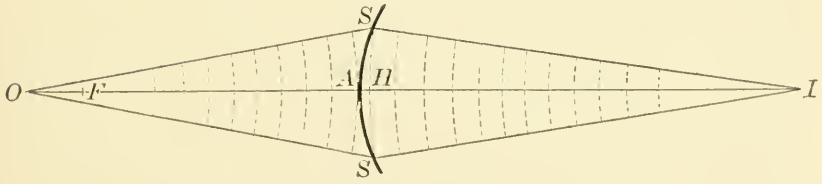
We have learned that the parallelism of rays is unaffected in refraction at a plane surface; but when parallel rays pass into a denser medium at a convex

FIG. 14.



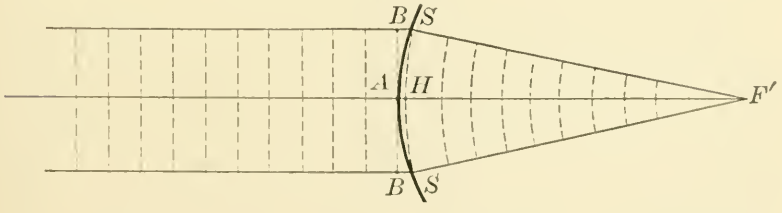
surface, the rays are rendered convergent, meeting in a point (Fig. 16) on the opposite side of the surface.

FIG. 15.



Similarly, a wave which, as the result of previous refraction, is converging to O (Fig. 17) will have its

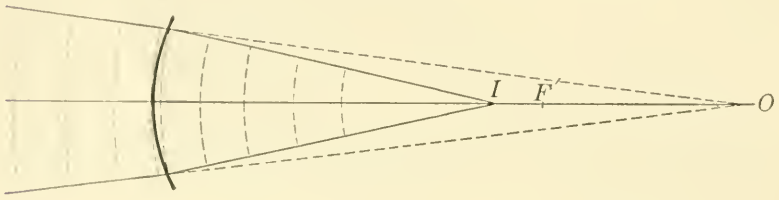
FIG. 16.



convergence increased by the refraction, so that it will afterward be concentrated at I; whereas, in refraction from a rarer to a denser medium at a *plane* surface

the convergence of an already converging wave would be diminished. These points of difference are readily understood if one bears in mind: (1) That a plane surface is one in which the curvature is reduced to zero; (2) that the convergence of the wave will be increased by refraction (or its divergence diminished) when the wave-curvature is opposite to or less than the surface-curvature; (3) that the wave will be un-

Fig. 17.

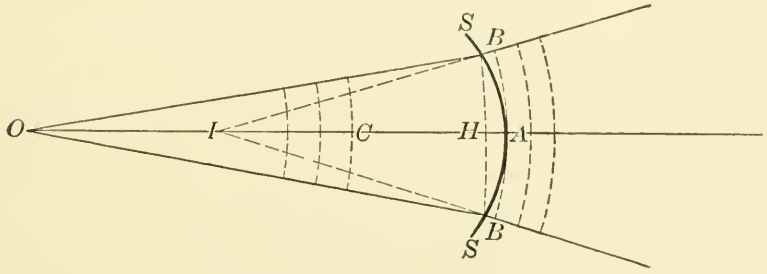


affected when the two curvatures are equal and in the same direction; and (4) that the convergence will be diminished when the wave-curvature is in the same direction and greater than the surface-curvature. Thus, if a wave is already converging to the centre of a spherical surface, none of the rays will be altered in direction, since they all meet the surface perpendicularly, or, since every part of the wave meets the surface at the same time. This corresponds to a plane wave passing into a second medium at a plane surface. Similarly, if the wave is converging to a point nearer than the centre of a convex surface, the convergence will be diminished by refraction, or, when the surface is plane, *any* convergent wave will have its convergence diminished in passing from a rarer to a denser medium.

Passage of a Spherical Wave from a Rarer to a Denser Medium at a Concave Surface.—The principle just enunciated applies equally to a concave surface, provided it is remembered that if a convex curva-

ture is considered as positive, a concave surface is algebraically negative, and that a numerically greater negative value is algebraically less than a smaller negative quantity; but to avoid this complicity, the preceding statements may simply be reversed—that is, in the passage of a wave from a rarer to a denser medium at a concave surface, the convergence of the wave is diminished (or the divergence increased) when the wave-curvature is opposite to or less than the surface-curvature, and divergence is diminished when the wave-curvature is in the same direction and greater than the surface-curvature. In Fig. 18 is illustrated

FIG. 18.



the increase of divergence which occurs when a wave proceeding from *O* (farther from the surface than the centre *C*) enters a denser medium at a concave surface; the refracted wave appears to proceed from *I*, which is nearer the surface than *O*.

Passage of a Spherical Wave from a Denser to a Rarer Medium at a Concave or Convex Surface.—It is apparent that the relation between the angles of incidence and refraction is not altered when these two angles exchange places in the diagrams, which, therefore, are applicable when the direction of wave motion is reversed. Hence, Figs. 13, 14, 15, 16 and 17 may be used to illustrate refraction in the passage of a wave from a denser to a rarer medium at a concave surface, such refraction corresponding in all respects with re-

fraction in the passage of a wave from a rarer to a denser medium at a convex surface. If (Fig. 13) a wave is converging to *I* before refraction, its convergence will be so increased by the refraction as to be concentrated at *O* after passing into the rarer medium at the concave surface; if (Fig. 14) the wave is plane (the rays parallel) before refraction, it will converge to the point *O* after entering the rare medium at the concave surface; if (Fig. 15) the wave diverges from *I*, it will converge to *O* after refraction; if (Fig. 16) the wave diverges from *F'*, it will be rendered plane by the refraction; and if (Fig. 17) the wave diverges from *I*, it will, after refraction, appear to diverge from *O*.

Similarly, Fig. 18 illustrates the refraction of a convergent pencil of light in its passage from a denser to a rarer medium at a convex surface; a wave converging to *I* would have its convergence so diminished in entering the rarer medium at the convex surface as to proceed to the point *O* after refraction.

Collective and Dispersive Refraction.—If we exclude those conditions (with which we are not especially concerned) in which the wave appears to proceed from or to be directed to the centre of the refracting surface, or to proceed from or to be directed to a point nearer the surface than the centre, it is apparent that the divergence of the wave is always diminished or its convergence increased by refraction in the passage of light from a rarer to a denser medium at a convex surface, or in its passage from a denser to a rarer medium at a concave surface; such refraction is called *convergent* or *collective*. But in the passage of light from a rarer to a denser medium at a concave surface or from a denser to a rarer medium at a convex surface the divergence of a wave is increased or its convergence is diminished; this is *divergent* or *dispersive* refraction.

Aberration.—As in refraction at plane surfaces, so at convex or concave surfaces, it is only when a small pencil of light is isolated that the refracted wave-front may be regarded as spherical in form and that all the rays may be regarded as meeting in a single point. When a large part of the wave passes into the second medium the angles of incidence of the rays increase so rapidly as the distance from the central ray (*axis*) increases that the more peripheral rays are refracted too much in proportion to the central rays; hence the meeting-point for the peripheral rays is nearer the surface than that for the central rays. This lack of unison is called *spherical* or *positive aberration*.

The cornea of the normal eye presents a diminishing curvature toward the periphery, resembling somewhat the small end of an ellipsoid, and in a surface of this form there is less aberration than in a spherical curvature.

In some cases of conical cornea the curvature at the apex is very great, with a rapid approach to the hyperboloidal form; in such curvature the great excess of central refraction causes the rays to meet nearer the surface than the peripheral rays. This is called *negative* aberration (Jackson).

Chromatic Aberration.—As in the passage of light through a prism the degree of refraction varies with the wave-length, so in refraction at spherical surfaces violet light is most deviated, and red the least so; consequently the various colors will not, strictly speaking, have the same meeting-point. This is *chromatic* aberration. It can be shown that both spherical and chromatic aberration occur in refraction by the eye, but not sufficiently to be noticeable in ordinary vision. In the construction of microscopes and other delicate optical instruments aberration (spherical and chromatic) is largely overcome by suitable arrangement and combination of lenses.

Foci.—In the consideration of small pencils, that is, upon the assumption that all the rays meet in a single point after refraction, the points at which the rays meet are called *foci*. The point from which they proceed before refraction is the *anterior* or *first* focus (or the *object*), and the point at which they meet or from which they appear to proceed after refraction is the *posterior* or *second* focus (or the *image*). The two foci together are called *conjugate* foci.

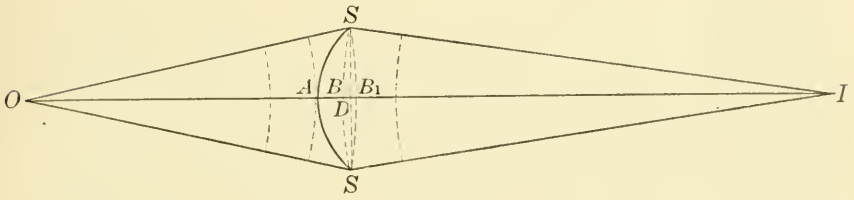
In Fig. 15 all the rays of the pencil proceeding from *O* are concentrated after refraction at *I;* hence, *I* is a brightly illuminated point, and it, as well as *O*, is an actual or *real* focus. But in Fig. 13 the refracted pencil only *appears* to proceed from *I;* no light is actually concentrated at this point, and in this case *I* is not a real, but an imaginary or *virtual* focus.

A real focus is an actual reproduction or image of the luminous point from which the wave proceeds, and as such this image may be depicted upon a screen, or upon a photographic plate, or upon the retina of the eye, where the light is transformed into a nerve-impulse conveying the sensation of vision. A virtual focus, not being an actually illuminated point, cannot be so reproduced.

Algebraic Relation between Conjugate Foci.—In order to pursue intelligently the study of refraction by the eye, it is requisite that the relation between conjugate foci be expressed in terms of an algebraic equation. Fig. 19 (expressing the same condition as in Fig. 15) is selected for the derivation of this equation because it is more convenient to regard all the terms as algebraically positive under these conditions—when light proceeds from a real focus, *O*, and converges after refraction to a real focus, *I*, the convexity of the surface being turned toward the incident wave. The straight line *O I* (the unrefracted ray) passing through the centre of the surface is called the *axis;* all distances

are measured on this line. $S\ A\ S$ is a section of the convex refracting surface; $S\ B_1\ S$ would represent the wave-front at a certain time, if the retarding medium were absent; but, owing to this retarding medium, the actual wave-front at this time is $S\ B\ S$. While the wave would have advanced from A to B_1 in the rarer medium, it is so retarded as to advance only as far as B in the denser medium. These distances are inversely proportional to the velocity of light in the two media; hence, if n represents the refractive index

FIG. 19.



of the first and n_1 that of the second medium, it is apparent that $n \cdot A\ B_1 = n_1 \cdot A\ B$. It also appears from the figure that $A\ B = A\ D - B\ D$, and that $A\ B_1 = A\ D + D\ B_1$; hence, $n\ (A\ D + D\ B_1) = n_1\ (A\ D - D\ B)$; or,

$$n \cdot D\ B_1 + n_1 \cdot D\ B = (n_1 - n)\ A\ D \qquad (a)$$

The distances $D\ B_1$, $D\ B$, and $A\ D$ are not in themselves practically measurable, but they respectively express the curvature of the incident and refracted waves and that of the refracting surface. If the arc $S\ B_1\ S$ is infinitesimal the bending or curvature of this arc will evidently be measured by the perpendicular distance $D\ B_1$; similarly, under the same conditions the curvature of the arcs $S\ B\ S$ and $S\ A\ S$ will be measured by $D\ B$ and $A\ D$ respectively. As the size of the arc increases, the perpendicular distance can no longer be taken as the exact measurement of the curvature, but for very small pencils of light, such

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as enter the pupil of the eye, any error arising from such measurements would be of no practical importance. But there are other and more convenient measurements which express the curvatures of the waves and of the surface: the inverse of their radii of curvature. Thus the curvature of the incident wave is expressed by $\frac{1}{OS}$; the curvature of the refracted wave is expressed by $\frac{1}{IS}$; and that of the refracting surface by $\frac{1}{r}$, r being the radius of this surface. Hence, these expressions could be substituted in equation (a) for $D\,B_1$, $D\,B$, and $A\,D$, respectively; but here still another substitution must be made which is only approximately correct: it must be borne in mind that the distances $O\,A$, $O\,S$, $I\,S$, and $I\,A$ are all very great in proportion to the arc $S\,A\,S$, and that consequently in actual measurement there would be very little difference between $O\,S$ and $O\,A$, and between $I\,S$ and $I\,A$.[1] These distances, $O\,A$ and $I\,A$, measured on the axis, may, therefore, be substituted for $O\,S$ and $I\,S$, respectively, and consequently for $D\,B_1$ and $D\,B$ in equation (a), which, therefore, becomes

$$\frac{n}{AO}+\frac{n_1}{AI}=\frac{(n_1-n)}{r}$$

or, substituting f and f' for $O\,A$ and $A\,I$, respectively,

$$\frac{n}{f}+\frac{n_1}{f'}=\frac{(n_1-n)}{r} \qquad (1)$$

This equation expressing the relation between conjugate focal distances (f and f') is, as has been shown, only approximately correct; it is, however, sufficiently

[1] The proper proportions cannot be represented diagrammatically.

so for the purposes of ophthalmological study, although it would be far from sufficient for the construction of microscopes or other instruments in which spherical aberration could not be neglected.

Within these prescribed limits this equation is applicable for all cases of refraction of a spherical (or plane) wave at a spherical (or plane) surface. When n_1 is greater than n, and r is positive, the refraction takes place in the passage of the wave from a rarer to a denser medium at a convex surface; when n_1 is less than n and r positive, the refraction is that of a wave passing from a denser to a rarer medium at a convex surface; when r is negative, the refracting surface is concave; and when r is infinite, the surface is plane.

Principal Foci and Focal Distances.—When O is so far distant from the surface that the wave may be regarded as plane and the rays as parallel, the distance $A\ O$ (f) must be regarded as infinite, and consequently $\frac{n}{f}$ must be zero. Making this substitution in equation (1), we derive for the corresponding value of f' the equation $f' = \frac{n_1\ r}{n_1 - n}$, from which we ascertain the focusing point for rays that are parallel before refraction. The distance ($A\ F'$ Fig. 16) of this point from the surface is the *posterior* (or second) *principal focal distance;* it is denoted by the letter F', the value of F' being, as just stated, derived from the equation $F' = \frac{n_1\ r}{n_1 - n}$. The point at which parallel rays are focused, as determined by this equation, is called the *posterior* (or second) *principal focus* (F', Fig. 16).

Similarly, if f' is infinite in equation (1), the corresponding value of f is $\frac{n\ r}{n_1 - n}$. This determines the point of origin of rays which become parallel after

refraction (F, Fig. 14). The distance $A\ F$ is the *anterior* (or first) *principal focal distance;* it is denoted by the letter F. The point (F, Fig 14) from which rays diverge in order to be rendered parallel after refraction is the *anterior* (or first) *principal focus*. Since $F = \frac{n\ r}{n_1 - n}$, equation (1) becomes $\frac{n}{f} + \frac{n_1}{f'} = \frac{n}{F} = \frac{n_1}{F'}$. (2)

If the index of the first medium is unity, as in air, this equation is still further simplified, being reduced to the form, $\frac{1}{f} + \frac{n}{f'} = \frac{1}{F}$, (3) in which n is the index of the second medium.

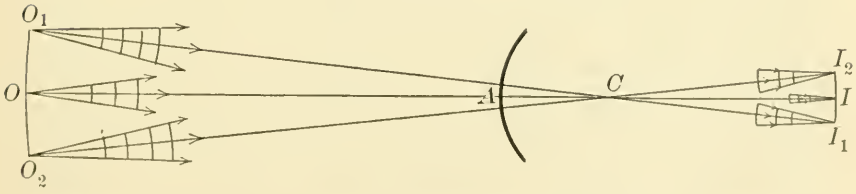
An examination of these equations shows that in convergent refraction both principal focal distances (F and F') are positive, indicating that both principal foci are real, as illustrated in Figs. 14 and 16; but in divergent refraction, n_1 being less than n and r positive, or n_1 being greater than n and r negative, both F and F' are negative. This indicates that both principal foci are virtual—that is, parallel rays will not be brought to a real focus by such refraction, but they will appear, after refraction, to proceed from a virtual focus (the second principal focus) lying in the first medium, and that rays directed toward the first principal focus, lying in the second medium, will be parallel after refraction.

It appears, further, that in convergent refraction the second conjugate focal distance (f') will always be positive when f is greater than the first principal focal distance; this indicates that *a real focus or image will be formed by convergent refraction when the point of origin of the wave is farther than the first principal focus from the surface* (including negative values of f, as illustrated in Fig. 17), the image in all cases lying in the second medium. When the point of origin is at the first principal focus, the rays will be

parallel after refraction, and no image will be formed. When the rays diverge from a point nearer the surface than the principal focus, they will appear to diverge after refraction from a point in the first medium, farther from the surface than the point of origin—that is, the divergence will be diminished but not entirely overcome (Fig. 13).

In divergent refraction a positive value of f will always give a negative value for f'—that is, rays proceeding from a point will never be united in a real focus by such refraction. The negative value of f' will be numerically less than the positive value of f, which indicates that the refracted wave will appear to diverge from a point nearer the surface than the point of origin of the incident wave (Fig. 18). When a wave is already converging to a point nearer to the surface than the first principal focus (lying in the second medium), the refracted wave will converge to a real focus: the convergence of the pencil will be diminished but not entirely overcome by the refraction.

FIG. 20.



Formation of Images by Refraction.—So far we have dealt only with single points of light; the manner in which objects of appreciable size are reproduced in images by refraction is illustrated in Fig. 20, in which O and I are conjugate points, lying on the axis $O\ I$. If this axis is turned about the centre C so as to describe the arcs $O_1\ O\ O_2$ and $I_1\ I\ I_2$, it is apparent that O_1 and I_1 are conjugate points, as are also O_2 and I_2. In other words, every point of the arc $O_1\ O\ O_2$

must have a corresponding conjugate point in the arc $I_1\ I\ I_2$, and $I_1\ I\ I_2$ is the image of $O_1\ O\ O_2$.

Practically, these arcs are so very small in comparison with the radii ($C'\ O$ and $C\ I$) that they differ inappreciably from straight lines, and it may be stated without noteworthy error that the image of a straight line $O_1\ O_2$ perpendicular to the axis at O will be a straight line $I_1\ I_2$ perpendicular to this axis at I; or, since this is true in any meridian, an object lying in a plane perpendicular to the axis will be reproduced in an image lying in a conjugate plane also perpendicular to the axis.

Any unrefracted ray (passing through the centre C'), as $O_1\ I_1$ or $O_2\ I_2$, is called a *secondary axis*, in contradistinction to $O\ I$, which is the *primary* or principal axis; unless otherwise stated, the latter is always indicated by mention of the axis of a refracting system.

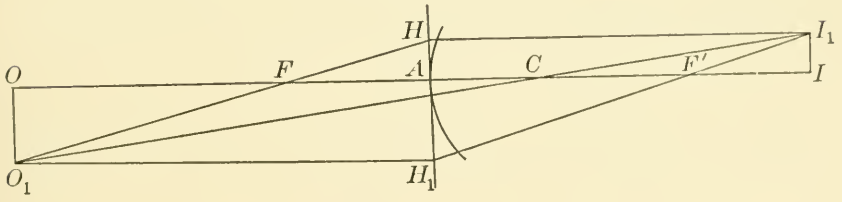
Cardinal Points and Planes.—Since every ray that passes through the centre C' (Fig. 20) is unrefracted, it is apparent that if the size of the object $O_1\ O_2$ is known, and also the positions of the centre C', and the conjugate I, it is possible to construct the image $I_1\ I_2$ by drawing the secondary axes $O_1\ I_1$ and $O_2\ I_2$ through the centre, and also to determine the size of the image from the similar triangles $O_1\ C'\ O_2$ and $I_1\ C'\ I_2$. If o represents the linear dimension of the object and i the corresponding dimension of the image, $i = o \cdot \frac{CI}{CO}$ or $i = o\,\frac{f' - r}{f + r}$ (*b*)

The centre (C') of the refracting surface is called the *optical centre*, or the *nodal point*, and, because of its relative importance, it is called a *cardinal point*. The other cardinal points of a single refracting surface are the two *principal foci*, and the *principal point* (A, Fig. 21), this being the point of intersection of the refracting surface and the primary axis. Planes erected

at these points, perpendicular to the axis, are the *cardinal planes*. These are the principal focal planes and the principal plane.

If the positions of the cardinal points have been determined, the position and size of the image of an object are readily ascertained. The way in which this is accomplished is illustrated in Fig. 21, in which $O\ O_1$ represents the linear dimension of an object (or one-half this dimension if the centre of the object lies on the axis), F and F' representing the two principal foci, and $H\ H_1$ the principal plane. Draw $O_1\ H_1$, representing a ray parallel to the axis $O\ I$; since all rays which are parallel to the axis before refraction

FIG. 21.



must pass through the posterior principal focus after refraction, $H_1\ I_1$, passing through F', represents the course of the refracted ray. Next draw $O_1\ H$, representing a ray passing through F, the anterior principal focus; such a ray must be parallel to the axis after refraction; it will be represented by $H\ I_1$. The point I_1 where the refracted rays intersect must be conjugate to O_1, and $I\ I_1$ will represent the image of $O\ O_1$.

It will be noticed that the rays have been drawn as if refracted, not at the curved surface, but at the principal plane. The error incurred by doing so is too slight to be of practical importance, since the focal distances are very great in comparison with the distance between the curved surface and the tangent plane. This substitution of the principal plane for the refract-

ing surface affords a convenient method of determining the size of the image. From the similar triangles $O\ F\ O_1$ and $A\ F\ H$ the following equation is derived : $\frac{HA}{A\ F} = \frac{OO_1}{OF}$, or, since $O\ O_1 = o$, $H\ A = I\ I_1 = i$, and $A\ F = F$, $i = o.\ \frac{F}{OF}$ (c)

Inversion of the Image.—It is apparent from the diagrams that in refraction real images are always inverted relatively to the object : virtual images are not inverted. Hence, if real images are regarded as algebraically positive, virtual images are negative, or *vice versa*.

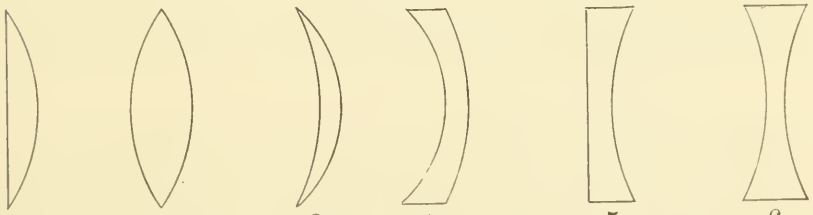
CHAPTER IV.

LENSES.

HAVING deduced the formula for the refraction of a small pencil of light at a spherical surface, we may apply this formula to any number of surfaces in succession, provided they are all centred on the same axis, for the image in the first refraction may be regarded as the object in the second refraction, and so on.

The simplest condition of multiple refraction is that effected by a symmetrical lens surrounded by air.[1] A

FIG. 22.



lens is defined as a portion of refracting substance bounded by one plane and one curved surface or by two curved surfaces, both centred on the same axis. Unless otherwise stated, it is always understood that the refractive index of the lens is greater than that of the surrounding medium.

Lenses are classified as (1) *plano-convex*, (2) *biconvex*, (3) and (4) *concavo-convex* or *convexo-concave*, (5) *plano-concave*, and (6) *biconcave* (Fig. 22). A

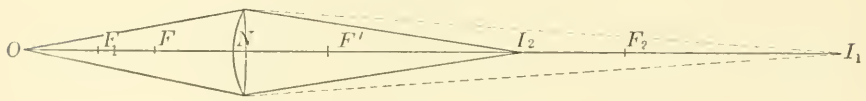
[1] Only spherical (symmetrical) lenses are considered in this chapter, cylindrical and toric lenses being considered in Chapter VIII.

concavo-convex lens is also called a *meniscus*, and in ophthalmology it is known as a *periscopic* lens, because, when the concave side is placed toward the eye, it affords a more extensive field of view than a plano-convex or a double convex lens.

The thickness of a lens is the distance between the two refracting surfaces as measured on the axis. In the lenses which are used as spectacles the thickness is so slight as compared with the focal measurements that it may be disregarded. Such lenses are called *thin*, in contradistinction to thick lenses, in which the distance between the two surfaces is proportionately too great to be ignored, as in the crystalline lens of the eye.

Algebraic Relation between Conjugate Points in Lens-refraction.—Refraction by a biconvex lens is

FIG. 23.



illustrated in Fig, 23, in which a wave diverging from O is represented as converging to I_1 as the result of refraction at the first surface of the lens, and as the result of the second refraction the wave which is converging to I_1 is rendered more convergent and is focused at I_2. This is only one of several conditions that may obtain: the wave may remain divergent after the first refraction, being rendered convergent by the second refraction (illustrated by reversing the course of the rays in the diagram); the wave may remain divergent or it may be plane after the two refractions; it may be plane or convergent before refraction, its convergence being increased by the refraction. The condition of a diverging pencil, brought to a real focus by the two combined refractions, as illustrated, is taken

as the typical case for the derivation of the formula, because it is more convenient to regard the focal distances as positive when the foci are real, as in the diagram.

Applying formula (3), page 52, to the first refraction, we derive the equation $\frac{1}{ON}+\frac{n}{NI_1}=\frac{n-1}{r}=\frac{1}{F_1}$ in which n, the refractive index of the lens, is greater than that of the surrounding air; r is the radius of curvature, and F_1 is the distance $(N F_1)$ of the lens from the principal focus (F_1) of this refraction.

Applying formula (3) to the second refraction, and remembering that as regards this refraction $N I_1$ is negative, as is also r_1, the radius of the surface, we derive $-\frac{n}{NI_1}+\frac{1}{NI_2}=\frac{1-n}{-r}=\frac{n-1}{r}=\frac{1}{F_2'}$, F_2 being the distance $(N F_2)$ from the lens to the principal focus (F_2) of the second refraction.

Adding these two equations, and replacing $O N$ and $N I_2$ by f and f', respectively, we derive

$$\frac{1}{f}+\frac{1}{f'}=(n-1)\left(\frac{1}{r}-\frac{1}{r_1}\right)=\frac{1}{F_1}+\frac{1}{F_2} \quad (4),$$

which expresses the relation between conjugate foci for all conditions of lens-refraction, provided the thickness of the lens may be disregarded.

If we make f infinite in the above equation, we derive $\frac{F_1 F_2}{F_1+F_2}$ as the corresponding value for the second principal focal distance, and if we make f' infinite, we derive this same value for the first principal focal distance; hence, in a lens the two principal focal distances are equal and (in thin lenses) the reciprocal of this distance $(\frac{1}{F})$ is equal to the sum of the reciprocals

of the principal focal distances $(\frac{1}{F_1} + \frac{1}{F_2})$ of the two separate refractions.

Making this substitution, equation (4) becomes $\frac{1}{f} + \frac{1}{f'} = \frac{1}{F}$ (5), which is the form in which the equation between conjugate points for lens-refraction is usually written.

In a plano-convex lens r_1 is infinite, and equation (5) becomes $\frac{1}{f} + \frac{1}{f'} = \frac{n-1}{r}$ (6). The same relation is derived, if, as with equal propriety, we make r infinite —that is, it is immaterial whether the plane or curved surface is turned toward the incident wave.

By modification in the sign of r or of r_1 or of both, these equations are equally applicable to plano-concave, convexo-concave, and biconcave lenses.

Collective Lenses.—It is apparent from examination of equation (5) that the principal foci are real in plano-convex, and in biconvex lenses, and in menisci in which the curvature of the concavity is less than that of the convexity. All such lenses are convergent or *collective* in action. It may be shown by further investigation of equation (5) that the action of a collective lens is determined by the following rule, which applies also to single-surface collective refraction, p. 52 :

1. A wave proceeding from a point will be brought to a real focus on the opposite side of the lens, so long as the point of origin of the wave is farther from the lens than the principal focus.

2. As the point of origin of the incident wave recedes from the lens, the conjugate focus on the opposite side approaches the lens, coinciding with the second principal focus when the incident wave becomes plane.

3. When the incident wave diverges from a point nearer the lens than the principal focus, the refracted

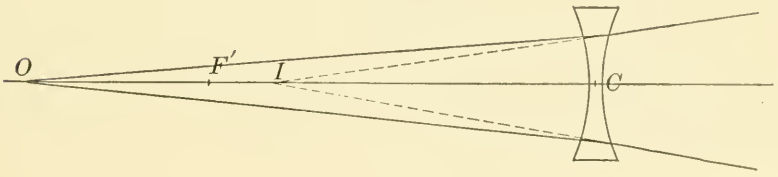
wave appears to proceed from a virtual focus on the same side of the lens and farther from it than the point of origin.

4. As the point of origin recedes from the lens, the virtual focus also recedes, being at an infinite distance (the rays parallel) when the incident wave diverges from the first principal focus.

5. When the incident wave is already converging toward a point behind the lens, the convergence is increased by the refraction, so that the refracted wave will be focused nearer the lens than the virtual focus toward which the incident wave is directed.

Dispersive Lenses.—The principal foci are virtual in plano-concave and biconcave lenses, and in menisci

FIG. 24.



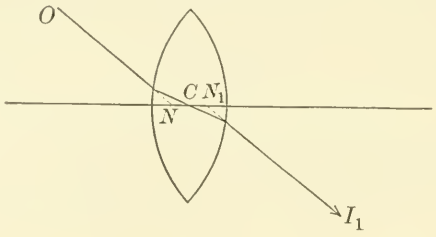
in which the curvature of the concavity is greater than that of the convexity. In the passage of light through all such lenses the effect is opposite to that just described—that is, the divergence of the wave is increased or its convergence is diminished (Fig. 24).

If the wave is plane before refraction, it appears, after passing through the lens, to proceed from the (second) principal focus, on the same side of the lens as the incident wave. If the incident wave diverges from a point, the refracted wave will appear to diverge from a point situated on the same side of the lens, and nearer than the point of origin of the incident wave. If the incident wave converges to such a degree as to be directed toward the first principal focus behind the lens, the rays will be rendered parallel by the refrac-

tion. Finally, if the incident wave converges to a point behind the lens and nearer the latter than the principal focus, the refracted wave will remain convergent, but its convergence will be less than that of the incident wave, the focus being farther from the lens than that of the incident wave.

Cardinal Points in Lens-refraction.—In refraction at a single surface all the rays which pass through the geometrical centre of the surface are unrefracted, but in lens-refraction any such ray, being unrefracted at one surface, would undergo refraction at the other, with the exception of the primary axis, which is per-

FIG. 25.

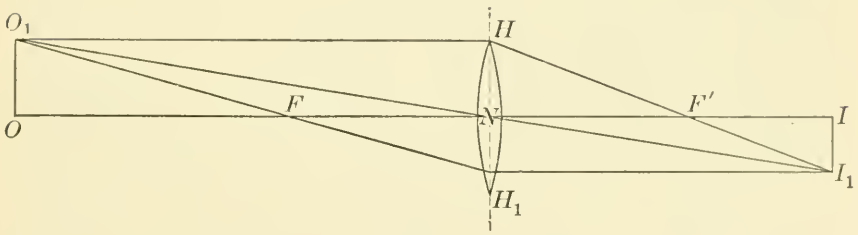


pendicular to both surfaces; *but the lens also has an optical centre*, such that any ray passing through it undergoes a lateral displacement (varying with the thickness of the lens), but undergoes no angular deviation; in other words, for all such rays the lens is equivalent to a plate with parallel faces. In Fig. 25, $O\ C\ I_1$ represents a ray passing through the optical centre C. Before entering the lens the ray is directed toward a point, N, on the primary axis; it is so refracted at the first surface as to pass through C, and after being refracted again at the second surface it appears to proceed from N_1. The angular deviations at the two surfaces exactly neutralize each other, so that $N_1\ I_1$ is parallel to $O\ N$. The two points N and N_1 are the *nodal points* of the lens, and C is the optical

centre. But when the thickness of the lens is disregarded, as in those lenses which we are considering, it is apparent that the lateral displacement of the nodal rays must also be disregarded, and the two nodal points are merged in a single nodal point at the centre of the lens. With this understanding, all rays which pass through the centre are unrefracted, constituting secondary axes. Similarly the principal points of the two refractions are merged in a single principal point, coinciding with the nodal point.

Hence the *cardinal points* of a thin lens are the two *principal foci*, and the *nodal point*. By means of these points the image of an object may be constructed in a manner similar to that described in refraction at a

FIG. 26.



single surface, the only difference being in the position of the nodal point, as illustrated in Fig. 26.

Numeration of Lenses.—Lenses are numbered in accordance with their focal length, or with their refractive power, the latter being inversely proportional to the former: if F expresses the focal length of a lens, $\frac{1}{F}$ expresses its refractive power.

Spectacle-lenses are usually made of glass whose index is about 1.52. If we regard this as being (approximately) 1.5, the focal length is twice the radius of curvature ($2\,r$) in plano-curved lenses, and in biconvex or biconcave lenses having an equal curvature at the two surfaces, the focal length is equal

to the radius of curvature of the surfaces ($F=r$). Hence, upon the assumption that the refractive index is 1.5, the equal curvature $(\frac{1}{r})$ which is ground on each face of such a lens may be taken as the measure of the lens. In this, the old method of numbering lenses, the inch is the unit of measurement, and the unit-lens is one whose focal length is *supposedly* 1 inch, having on each face a curvature whose radius is 1 inch.

There are several serious disadvantages in this method; in the first place, the inch is not a fixed unit, varying considerably in different countries; secondly, owing to the fact that the refractive index is greater than 1.5, the focal length is in reality less than is indicated by the radius of curvature, in accordance with which the lenses are numbered; and, thirdly, owing to the comparatively great refractive power of the unit-lens, the power must be expressed as a fraction in all those lenses which are commonly used in ophthalmology. Thus, a lens having a focal length of 20 inches has a power $\frac{1}{20}$ as great as that of the unit-lens; the power of a 40-inch lens (having a focal length of 40 inches) is expressed by $\frac{1}{40}$, and so on. These fractional expressions are very inconvenient in the addition or combination of lenses, since the combined action of two thin lenses placed in apposition is equal to the sum of the powers of the two lenses.[1]

All these disadvantages are overcome in the metric system of numbering lenses, which was introduced by Nagel in 1866. In this system the *dioptre* (Monoyer) is the unit of refractive power. The dioptre (1 D.) expresses the power of a lens whose focal length is 1 metre; 2 D. expresses the power of a lens having a

[1] This results from the equation $\frac{1}{F} = \frac{1}{F_1} + \frac{1}{F_2}$, since any thin lens may be replaced by two plano-curved lenses (whose focal lengths are F_1 and F_2, respectively), having their plane faces in apposition.

focal length of $\frac{1}{2}$ metre; 0.5 D. is the power of a lens having a focal length of 2 metres; 0.25 D. is the power of a lens having a focal length of 4 metres, and so on.

Although this method has entirely displaced the inch system, it is important to be able to transform the lens-number from one system to the other. To do this it is only necessary to remember that 1 metre is equivalent (approximately) to 40 English or to 36 Paris inches, and that the focal length, as expressed in inches, will be indicated by 40 (or 36) times as many units as when expressed in metres. Thus, a lens having a focal length of 1 metre (1 D.) will be measured by the number 40 (a 40-inch lens) in the English inch system; the focal length ($\frac{1}{3}$ metre) of a lens of 3 D. will be expressed by $\frac{40}{3}$ in inches, or approximately it will represent a 13-inch lens. In other words, since the focal length *in metres* is expressed by the reciprocal of the dioptric number of the lens, the number of the lens in the inch system is obtained by dividing 40 (or 36, if Paris inches) by the dioptric number of the lens. Conversely, the dioptric number is obtained by dividing 40 (or 36) by the lens-number as expressed in inches.

CHAPTER V.

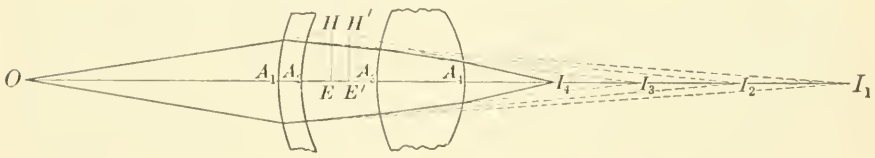
COMPOUND OPTICAL SYSTEMS.

THE EYE.

In deducing the formula for thin lenses the algebraic equations were much simplified by disregarding the thickness of the lens and measuring all quantities from a common point (the centre of the lens); but in deriving the general relation between conjugate foci in the refraction at a number of surfaces we cannot ignore the intervals between these surfaces.

A series of spherical surfaces, separated by intervals, the surfaces all being centred on a common axis, constitutes a *compound optical system*. Refraction by a

Fig. 27.



Refraction by a compound optical system.

compound system is illustrated in Fig. 27, O being the point on the axis from which the incident wave proceeds. At the first surface, A_1, the refraction is such that the wave converges to the focus I_1, but before reaching this focus it is refracted at the second surface, A_2, so that it converges toward I_2; at the third surface it is refracted toward I_3, and so on for any number of surfaces. In the first refraction A_1 O and A_1 I_1 are conjugate focal distances, both posi-

tive; in the second refraction $A_2 I_1$ and $A_2 I_2$ are conjugate focal distances, $A_2 I_1$ being negative, since the incident wave is already converging to the focus I_1; in the third refraction $A_3 I_2$ and $A_3 I_3$ are conjugate, $A_3 I_2$ being negative, and so on for any number of refractions.

Applying equation (2), page 52, to these successive refractions, continuing the process to four surfaces, we have the following equations:

$$\frac{1}{OA_1} + \frac{n_1}{A_1 I_1} = \frac{n_1 - 1}{r_1} = \frac{1}{F_1} \quad (1)$$

$$-\frac{n_1}{A_2 I_1} + \frac{n_2}{A_2 I_2} = \frac{n_2 - n_1}{r_2} = \frac{1}{F_2} \quad (2)$$

$$-\frac{n_2}{A_3 I_2} + \frac{n_3}{A_3 I_3} = \frac{n_3 - n_2}{r_3} = \frac{1}{F_3} \quad (3)$$

$$-\frac{n_3}{A_4 I_3} + \frac{n_4}{A_4 I_4} = \frac{n_4 - n_3}{-r_4} = \frac{1}{F_4} \quad (4)$$

In these equations the index of air, the first medium, is unity; the indices of the successive media are n_1, n_2, n_3, and n_4; the radii of curvature are represented by r_1, r_2, r_3, and r_4. These radii are considered positive when the surfaces are convex to incident light and negative when they are concave to incident light. Let the intervals between the surfaces (the thicknesses) be denoted by t_1, t_2, and t_3; then it appears from the figure that $A_2 I_1$ is equal to $A_1 I_1 - t_1$; that $A_3 I_2$ is equal to $A_2 I_2 - t_2$; and that $A_4 I_3$ is equal to $A_3 I_3 - t_3$, and so on.

Making these substitutions, we derive:

From (1) $$\frac{1}{OA_1} = -\frac{n_1}{A_1 I_1} + \frac{1}{F_1} \quad (1a)$$

From (2) $$\frac{A_1 I_1}{n_1} = \frac{t_1}{n_1} + \frac{1}{\frac{n_2}{A_2 I_2} - \frac{1}{F_2}} \quad (2a)$$

$$\text{From (3)} \quad \frac{A_2I_2}{n_2} = \frac{t_2}{n_2} + \frac{1}{\frac{n_3}{A_3I_3} - \frac{1}{F_3}} \qquad (3a)$$

$$\text{From (4)} \quad \frac{A_3I_3}{n_3} = \frac{t_3}{n_3} + \frac{1}{\frac{n_4}{A_4I_4} - \frac{1}{F_4}} \qquad (4a)$$

From these four equations we may, by the elimination of the intermediate terms, find the relation between the focus O and its conjugate I_4 after refraction by a compound system of four surfaces. If there are but three surfaces, equations $(1a)$, $(2a)$, and $(3a)$ suffice, and if there are but two surfaces, as in a thick lens, equations $(1a)$ and $(2a)$ establish the relation between conjugate foci. If, on the other hand, there are more than four surfaces, we must write out an additional equation for each additional surface.

The Surfaces and Media of the Eye.—*The anterior surface of the cornea* is the first surface at which light undergoes refraction in its passage through the media of the eye. This surface is convex to incident light, and the refractive index of the corneal tissue is greater than that of the air from which light proceeds; hence the refraction which takes place at this surface is convergent.

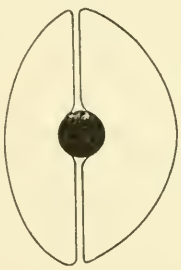
The posterior surface of the cornea, at which light passes into the aqueous humor, is the second refracting surface. This surface is also convex, its curvature being slightly greater than that of the anterior surface; but in this case the light is passing from a denser to a rarer medium, since the index of the aqueous humor is less than that of the cornea. The effect of this refraction is, therefore, a partial neutralization of the convergent action of the anterior surface.

The anterior surface of the crystalline lens is the third surface at which light is refracted. This also is a convex surface, and the index of the lens is greater

than that of the aqueous humor; hence, the convergence of refracted pencils is still further increased in passing into the lens.

The crystalline lens is not a homogeneous substance; its refractive index gradually increases from the outer to the central part of the lens. It is necessary, therefore, for the purpose of calculation to substitute for the physiological lens an ideal lens which shall have the same refractive effect as the former. Helmholtz and others have, by very exact measurements, been enabled to determine the refractive power of the human lens, whereby it is possible to substitute for the natural lens an equivalent lens having the same curvatures and thickness as the former, but a uniform index.

FIG. 28.



The equivalent index of the lens is not, however, the average of the indices of the component portions; it is greater than the greatest index of the natural lens. This is because the curvature of the central part (nucleus) of the lens is greater than that of the total lens. The physiological lens may be regarded as composed of the nucleus with the addition of two divergent menisci, applied as is illustrated in Fig. 28. If the entire lens had the index of the nucleus, the divergent effect of these two menisci would be greater than it is in the real lens, in which the outer portions—the divergent menisci—have a lower index than the

nucleus. Hence, in the equivalent lens the index must be greater than that of the most highly refracting part of the physiological lens.

The posterior surface of the crystalline lens, at which light enters the vitreous body, is concave to incident light, and the index of this body is less than that of the lens; hence the refraction which takes place at this surface is convergent. This is the last surface which need be considered, since there is no appreciable refraction in the passage of the rays from the vitreous to the deeper layers of the retina.

There are thus in the eye (substituting the equivalent for the natural lens) four refracting surfaces, all of which exert a convergent action except the posterior surface of the cornea, and the divergent effect of this surface is very slight as compared with the convergent action of the other surfaces. Assuming, therefore, that the surfaces of the eye are spherical and all centred on a common axis—that is, that the eye constitutes a regular compound optical system—it is apparent that any pencil of light proceeding from a point without the anterior focus of the system will be brought to a real focus at some point behind the cornea.

The following table gives the average values of the curvatures of the surfaces of the human eye, the intervals between these surfaces, and the indices of the media:

Radii of Curvature.			
Anterior surface of the cornea		7.8 mm.	(r_1)
Posterior surface of the cornea		6 mm.	(r_2)
Anterior surface of the lens		10 mm.	(r_3)
Posterior surface of the lens		6 mm.	(r_4)
Indices.		*Thicknesses.*	
Cornea	1.377 (n_1)	1 mm.	(t_1)
Aqueous humor	1.337 (n_2)	2.6 mm.	(t_2)
Lens	1.438 (n_3)	4 mm.	(t_3)
Vitreous body	1.337 (n_4)		

The Schematic Eye.—If we substitute the numerical values here given in the equations (1a), (2a), (3a),

and (4*a*), we derive an equation expressing the relation between conjugate points in the average or schematic eye.

Making the proper substitutions, we derive the following relations:

$$\frac{1}{F_1} = \frac{n_1 - 1}{r_1} = 0.0484\,; \qquad \frac{1}{F_2} = \frac{n_2 - n_1}{r_2} = 0.0066\,;$$

$$\frac{1}{F_3} = \frac{n_3 - n_2}{r_3} = 0.0101\,; \qquad \frac{1}{F_4} = \frac{n_4 - n_3}{-r_4} = 0.0168\,;$$

$$\frac{t_1}{n_1} = 0.7262\,; \qquad \frac{t_2}{n_2} = 1.9446\,; \qquad \frac{t_3}{n_3} = 2.7816.$$

Substituting 0.0168 for $\frac{1}{F_4}$, and 2.7816 for $\frac{t_3}{n_3}$, equation (4*a*) becomes (writing f_4 for $A_4\ I_4$):

$$\frac{A_3\ I_3}{n_3} = 2.7816 + \frac{1}{\frac{n_4}{f_4} - 0.0168} =$$

$$\frac{2.7816\ n_4 + 0.9533 f_4}{n_4 - 0.0168\ f_4} \qquad (4b)$$

Substituting this value of $\frac{n_3}{A_3\ I_3}$ in equation (3*a*), replacing $\frac{t_2}{n_2}$ and $\frac{1}{F_3}$ by their numerical values, we derive:

$$\frac{A_2\ I_2}{n_2} = \frac{4.6717\ n_4 + 0.902\ f_4}{0.972\ n_4 - 0.0264\ f_4} \qquad (3b)$$

In the same manner we derive:

$$\frac{A_1\ I_1}{n_1} = \frac{5.4\ n_4 + 0.887\ f_4}{1.0028\ n_4 - 0.0205\ f_4} \qquad (2b)$$

And (writing f_0 for $O\ A_1$):

$$\frac{1}{f_0} = \frac{0\ 7415\ n_4 - 0.0634\ f_4}{5.4\ n_4 + 0.887\ f_4} \qquad (1b)$$

Equation (1*b*) expresses the relation between the position of the point O (Fig. 27), from which a pencil of light proceeds, and its conjugate, I_4, after refraction at the four surfaces of the eye. This relation is expressed in terms of f_0, which measures the distance of O from the first surface (the anterior surface of the cornea) and of f_4, which measures the distance of I_4 from the last surface (the posterior surface of the lens).

Position of the Posterior Principal Focus of the Eye.—Since equation (1*b*) is a general equation, true for all conjugate foci, the position of the posterior principal focus may be determined by making f_0 infinite. In this case $\frac{1}{f_0}$ is equal to zero, and the equation becomes $0.0634\, f_4 = 0.7415\ n_4 = 0.7415 \times 1.337 = 0.9913$; from which is derived $f_4 = 15.63$—that is, the posterior principal focus lies 15.63 mm. behind the posterior surface of the lens. Since the latter surface lies 7.6 mm. behind the anterior surface of the cornea, the principal focus is situated 23.23 mm. behind this surface.

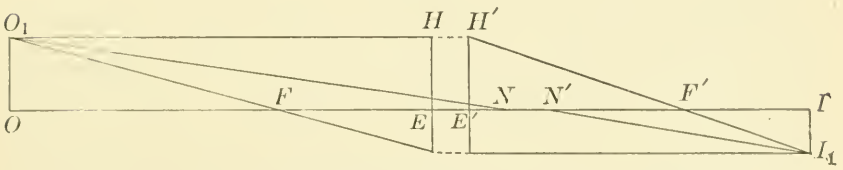
Position of the Anterior Principal Focus.—In a similar manner, by assigning an infinite value to f_4, the anterior principal focus is found to lie 13.99 mm. in front of the cornea.

Principal Points and Planes of the Eye.—In our study of refraction at single surfaces and by thin lenses we learned that the size of the image could be determined by a simple geometrical construction, the requisite data being the size of the object and the positions of the two principal foci and of the principal point. It was first demonstrated by the eminent mathematician Gauss that this same construction may be applied to a compound system, whatever may be the number of surfaces; but, instead of measuring all distances from one point, as in simple systems, we must measure them from *two principal points*, separated by an interval which varies with the system.

The principal points are conjugate to each other in the refraction by the entire system; hence, any incident ray directed toward the first principal point will, after passing through the system, appear to proceed from the second principal point. Moreover, these points are so situated that the conjugate focal planes erected through them (the principal planes) bear the same relation to the system that the single principal plane bears to the simple system.

The principal planes may, therefore, be defined as conjugate focal planes, so situated that any incident ray directed toward a point in the first plane will, after refraction by the entire system, appear to proceed from

FIG. 29.



Diagrammatic construction of the image by means of the cardinal points and planes.

a point in the second plane, the two points of intersection lying on the same side of the axis and at the same distance from it. This is illustrated in Fig. 27, in which $H\,E$ represents the first and $H'\,E'$ represents the second principal plane. The manner in which these planes are utilized in determining the size of the image is illustrated in Fig. 29.

The positions of the principal points can be deduced for any refracting system by combining the condition of equality of $H\,E$ and $H'\,E'$ with the relation between conjugate points. The algebraic process must be omitted here, as it is somewhat tedious; moreover, it is not practically necessary, for (as an examination of the general formula would show) equation (1*b*), page 71,

contains all the data required for a complete solution of the system.[1]

The numerical coefficient of f_4, as it occurs in the numerator of equation (1*b*), expressing the relation between conjugate points, is always equal to $\frac{1}{F}$, F being the anterior principal focal distance—that is, the distance between the first principal point and the anterior principal focus. Thus, for our schematic eye F is equal to $\frac{1}{0.0634}$, or the anterior principal focus lies 15.77 mm. in front of the first principal point. We have already ascertained that the anterior focus lies 13.99 mm. in front of the cornea; hence the first principal point must be situated 1.78 mm. behind the anterior surface of the cornea.

Having determined F the anterior focal distance, the posterior focal distance, as measured from the second principal point, is ascertained by multiplying the value of F by the refractive index of the final medium (the vitreous), for the same algebraic relation which exists between conjugate foci in a simple system exists also in a compound system when the focal distances are measured from the principal points. Thus the distance (F') from the posterior focus to the second principal point is found to be 21.08 mm.; and since the posterior focus lies 23.23 mm. behind the anterior surface of the cornea, the second principal point must lie 2.15 mm. behind this surface.

Algebraic Relation between Conjugate Foci.—When the first and second conjugate foci are measured from the first and second principal points, respectively, the relation between conjugate foci is expressed by the equation $\frac{1}{f} + \frac{n}{f'} = \frac{1}{F}$, as in simple systems. If l and

[1] The algebraic solution of the compound optical system may be found in the author's "Handbook of Optics," Chapter IV.

l' denote the distances of the first and second conjugate foci from the first and second *principal foci*, respectively, the foregoing equation may be reduced to the form $l\,l' = F\,F'$, which is a convenient formula for determining the relative position of conjugate foci.[1]

The Nodal Points.—We have learned that a single refracting surface and a thin lens each has a nodal point, the property of which is that a ray passing through this point undergoes no change of direction. In a compound system there are *two nodal points*, separated by the same interval that separates the two principal points. An incident ray directed toward the first nodal point is so refracted by the system that the emergent ray appears to proceed from the second nodal point *and in a direction parallel to the incident ray.*

The diagrammatic construction of a compound system by means of the principal and the nodal points is illustrated in Fig. 29. The position of the first nodal point is found by measuring from F (the anterior focus) the distance $F\,N$, *equal to the posterior focal distance;* the point N represents the first nodal point. Similarly, the position of the second nodal point is found by measuring from F' (the posterior focus) the distance $F'N'$, *equal to the anterior focal distance;* N' represents the second nodal point. When N and N' are situated in accordance with these measurements it is easily proved geometrically that $O\,N\,O_1$ and $I\,N'\,I_1$ are similar triangles, and consequently $N'\,I_1$ is parallel to $O_1\,N$. That N' is conjugate to N may also be proved by assigning the proper value to f ($f = -E\,N$) in the equation $\frac{1}{f} + \frac{n}{f'} = \frac{1}{F.}$ Since, therefore, N and N' are conjugate, as are also O_1 and I_1, it is apparent that if $O_1\,N$ represents an

[1] In lens-refraction this equation becomes $l\,l' = F^2$, since $F = F'$.

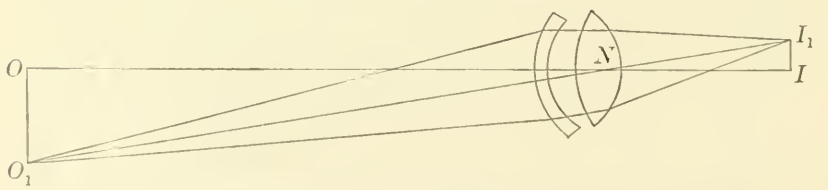
incident ray, $N' I_1$ must represent the corresponding emergent ray.

When, in a compound system, n, the final index of refraction, is the same as that of the first medium, as in refraction by a *thick lens or a system of lenses*, F is equal to F', and, consequently, the nodal points coincide with the principal points.

In the schematic eye the first nodal point, as determined in accordance with the foregoing instructions, lies 21.08 mm. behind the anterior focus, or 7.09 mm. behind the anterior surface of the cornea, and the second nodal point lies 7.46 mm. behind this surface. It thus appears that the nodal points very nearly coincide in position with the posterior surface of the lens.

Since in the eye the two nodal points are separated by so slight an interval (0.37 mm.), a ray directed toward the first nodal point undergoes an almost inappreciable lateral displacement; in fact, these points are so near together that for practical purposes they may be regarded as merged in a single nodal point, coinciding with the optical centre (Fig. 30), through which the ray passes.

FIG. 30.



Illustrating the projection of the retinal image along the nodal ray.

Rectification and Projection of Retinal Images. —Since in refraction all real images are inverted, it is apparent that the images of all external objects as formed on the retina must be inverted relatively to

the objects; but objects as perceived by the visual sense appear in their true relations: the retinal image itself does not enter into consciousness, but the mind has learned from experience that stimulation received through certain fibres (these being connected with a certain part of the retina) always corresponds to an object situated in a certain direction. Thus, light proceeding from an object on the left can only stimulate the right side of the retina, and *vice versa*. Similarly, an object situated above the eye stimulates the lower side of the retina, and *vice versa*.

The relative direction of any point in space from its image on the retina can be expressed only by the straight line which joins these two points. The nodal ray connects these two points, and, moreover, it is a straight line except for an almost inappreciable lateral displacement; hence, this line approximately represents the line of visual projection (Fig. 30).[1]

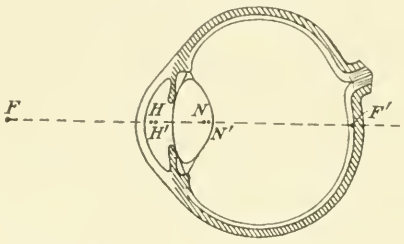
Relative Size of Object and Image.—The relation between the size of an object and its image in a compound system is precisely the same as if the two principal points were not separated by an interval, for we deduce from the similar triangles (Fig. 29) the equation $\frac{o}{i} = \frac{OF}{F}$ and $\frac{o}{i} = \frac{ON}{IN'}$ which are the same relations as were found to exist in simple systems.

It is apparent from the first of these equations that in comparing the size of the image as formed in dif-

[1] There is no reason for believing that the mind is capable of judging of the direction from which the wave-motion proceeds, except so far as this is inferred from the part of the retina stimulated. Furthermore, the assumption that the line of projection corresponds with the axis of the stimulated retinal element (*retinal radius theory of projection*) is untenable, because projection along this line would lead to erroneous judgment as to the position of objects lying in the periphery of the field of vision; that is, a straight line drawn from the image and in the direction of the axis of the retinal element (or at right angles to the surface of the retina) would not pass through the object, and consequently it could not indicate its direction.

ferent systems the linear dimension (i) is always proportional to the anterior focal distance (F), provided the distance ($O\,F$) of the object from the anterior focus remains unchanged. This assumption is permissible in comparing the size of images as formed in different refractive conditions of the eye.

FIG. 31.



The schematic or *average* normal eye (*natural size*). The anterior and posterior principal foci are represented by F and F' respectively; the first and second principal points by H and H', and the nodal points by N and N'.

For convenience of reference the distances of the cardinal points of the schematic eye from the summit of the cornea and from the principal points are here re-stated as they have been determined in the preceding calculations (Fig. 31):

From summit of cornea to first principal point . . .	1.78 mm.
From summit of cornea to second principal point . .	2.15 mm.
From summit of cornea to first nodal point	7.09 mm.
From summit of cornea to second nodal point . . .	7.46 mm.
From summit of cornea to anterior focus	13.99 mm.
From summit of cornea to posterior focus	23.23 mm.
Anterior focal distance (measured from first principal point)	15.77 mm.
Posterior focal distance (measured from second principal point)	21.08 mm.

The Reduced Eye.—The interval which separates the two principal points (and the two nodal points) of the eye is only 0.37 mm. in length; and if we disregard this interval, the refraction by the eye is in all respects comparable to that which would be produced

by a simple system of one surface, the indices of the two media being those of the first and last media of the compound system. The curvature of the equivalent imaginary surface would be obtained from the equation $r = (n - 1) F$.

We may thus for the study of ocular refraction substitute such a simple system, placing the imaginary surface at the first principal point. So far as the size of images is concerned, there will be no difference between the compound system (the schematic eye) and its substitute; but as regards the position of images, we must remember that in the compound system all posterior focal distances are measured from the second principal point, 0.37 mm. from the first principal point, and this interval must be added to any conjugate focal distance, as derived from the simple system, in order to determine the position of the conjugate focus in the compound system.

Listing's Reduced Eye.—Listing, who first reduced the schematic eye to a simple equivalent, did not place the imaginary surface at the first principal point, but between the two principal points, the two principal foci of the schematic eye retaining their positions. Consequently, in this substitution the focal distances of the reduced eye are not strictly identical with those of the schematic eye; the discrepancy, however, is too slight to be of practical importance. But Listing's schematic eye, on which his reduction is based, is too short to represent accurately the normal human eye.[1]

Donders' Reduced Eye.—Of the several other equivalents which have been proposed for the schematic eye, the only one requiring special mention is that of Donders. In this the anterior focal distance is 15 mm., the posterior focal distance is 20 mm., and the radius of curvature is 5 mm. From the equation

[1] This is mainly because of the adoption of too high a refractive index (1.4545) for the lens.

$r = (n - 1) F$, n is found to be equal to 1.333, which is the index of water.

While this system does not replace the schematic eye with mathematical accuracy, it furnishes very convenient data for the construction of an artificial eye for the study of refraction.

The Aphakic Eye.—When the crystalline lens is absent from the eye the latter is said to be *aphakic*. In this condition, in which light passes directly from the aqueous to the vitreous without the intervention of the lens, the focal distances of the eye differ materially from those of the schematic eye.

Since the aqueous and vitreous have practically the same refractive index, the aphakic eye presents only two surfaces—the anterior and posterior surfaces of the cornea; hence, to deduce the cardinal points of this eye we need only equations (1) and (2), p. 67. But the corneal refraction is the basis of calculations of great practical importance in keratometry, and it is, therefore, necessary to reduce this refraction to a system of one surface. This is done by disregarding the posterior surface of the cornea and assigning to the cornea the lower index (1.337) of the aqueous humor. In this way is counterbalanced, in great part, but not entirely, the divergent action of the posterior corneal surface, this divergent action not being so slight as is generally believed.[1]

Focal Distances of the Aphakic Eye.—From the equation $F = \frac{r}{n - 1}$ the anterior focus of the aphakic eye is found to lie 23.14 mm. in front of the cornea; and from $F' = \frac{n r}{n - 1}$ the posterior focus is found to lie 30.94 mm. behind the anterior surface of the cornea.

[1] Tscherning's Phys. Optics (American edition), p. 32.

Relative Position of the Retina and Posterior Focus.—When the retina intersects the optic axis of the eye at its posterior focus the eye is adapted to receive a clear impression of a distant object. This condition, occurring during complete relaxation of the ciliary muscle, is called *emmetropia*. Any deviation from emmetropia is called *ametropia*.

Hyperopia is that form of ametropia in which the retina lies in front of the posterior focus when the ciliary muscle is relaxed. In this condition the image of a distant object, as formed on the retina, will be blurred; that of a near object will be more so.

Myopia is that condition in which the retina lies behind the posterior focus when the ciliary muscle is relaxed. In the myopic eye the image of a distant object is blurred, but that of a near object may be clearly formed on the retina.

Accommodation.—In the refraction by the eye the position of the image is not appreciably altered by changing the distance of the object, provided this distance is not less than (about) 6 metres (20 feet); that is, for all distances exceeding this limit the image is formed at the posterior principal focus. But when an object is nearer than this its conjugate image falls perceptibly behind the principal focus, and consequently behind the retina if the eye is emmetropic, and more so if the eye is hyperopic.

In order that a near object may be clearly seen, the image must be brought forward so that it will be focused on the retina. This is normally accomplished by an increase in the convexity of the crystalline lens under the influence of the ciliary muscle. This adaptation of the eye for various distances is called *accommodation*.

Since accommodation is effected by change in curvature of the lens, the optical system of the eye varies, in near vision, with every variation in the distance

of the object. The focal distances are shortened by accommodative action, so that the retina lies behind the principal focus, as in myopia.

In hyperopia accommodative action is exercised even in distant vision, in order to bring the posterior principal focus forward to the retina, thus rendering possible a clear impression. By a still further increase of curvature, provided sufficient accommodative power is available, the hyperopic eye may be adapted for near vision.

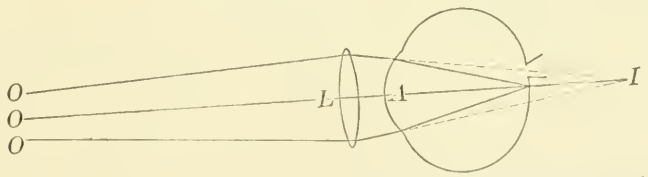
In myopia no accommodation is required for near vision, unless the object lies nearer than the anterior conjugate to the retina (*I*, Fig. 33), as determined in relaxation of the ciliary muscle.

CHAPTER VI.

THE USE OF LENSES IN AMETROPIA.

Since in hyperopia, if unaided by accommodation, the principal focus lies behind the retina, only such pencils as are already converging when they enter the eye can be focused on the retina. Thus, if *I*, Fig. 32, is conjugate to the retina, a pencil which is converging toward *I* will be so refracted by the eye as to be focused on the retina. In order that the rays from any point, *O*, may receive the necessary convergence, a convex lens, *L*, must be placed before the eye, so that in the refraction by the lens alone *I* is conjugate to *O*.

Fig. 32.



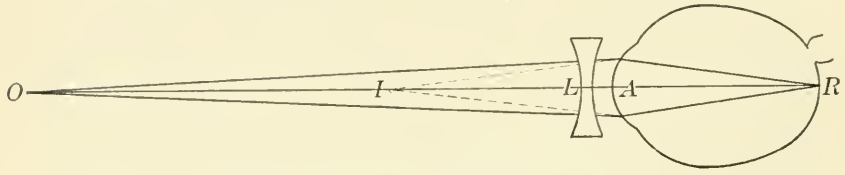
Correction of hyperopia with a convex lens. The point *O*, from which the rays diverge, is too far distant to be represented in the diagram.

When the object *O* is not less than 6 metres from the lens, the rays may be regarded as parallel; in this case *I* is the principal focus and *L I* is the focal length of the lens which corrects the hyperopia.

In myopia rays from a distant point, *O*, Fig. 33, will be brought to a focus in front of the retina; and in order that the image may be focused on the retina, the rays which diverge from *O* must be made to enter the eye as if diverging from *I*, which is conjugate to the retina. This may be accomplished by a concave lens,

L, of such strength that in the refraction by the lens alone I is conjugate to O. When O is so far distant that the rays may be regarded as parallel, I represents the principal focus, and $L\,I$ the focal length of the lens which corrects the myopia.

FIG. 33.



Correction of myopia with a concave lens.

Far-point of the Eye.—The point I, which is conjugate to the retina, is called the far-point, for the image of any more distant point will lie in front of the retina, and distinct vision under this condition is impossible. In hyperopia I lies behind the eye (Fig. 32); that is, the far-point is negative.

Effect of Changing the Position of the Correcting Lens.—When a convex lens is placed before the eye in order to cause the image of an object (O, Fig. 32) to fall upon the retina, O and I are conjugate points in the refraction by the lens. These two points are fixed, but the lens may have any position between A and O. It may be proved, both experimentally and mathematically, that for any lens the line $O\,I$ between conjugate points is shorter when the lens occupies a midway position between these points than in any other position. Conversely, for the fixed points O and I a weaker lens will suffice when this is placed midway between O and I than in any other position.

When the lens occupies this midway position the two conjugate focal distances $L\,O$ and $L\,I$ are each equal to twice the focal length of the lens. Hence, it is apparent that increasing the distance between the

eye and the lens increases the correcting power of a convex lens so long as the distance of the lens from the object is more than twice the focal length of the lens, and that when this distance is less than twice the focal length of the lens, increasing the distance between the eye and lens diminishes the correcting power of the latter.

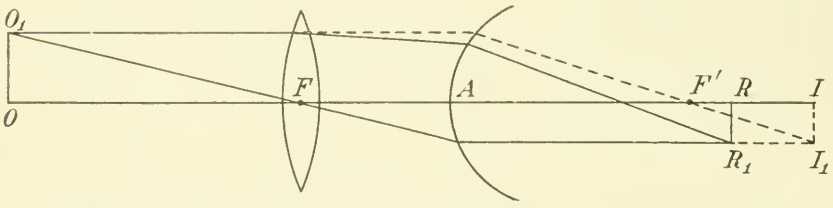
In the adaptation of the hyperopic eye for distant vision the distance of the lens from the object is more than twice the focal length of the lens; consequently, a lens which corrects the hyperopia in one position will be too strong or too weak according as it is moved away from or toward the eye; but when the object is near the lens, as in the use of reading glasses, the distance between the object and lens is usually less than twice the focal length, and a change in position of the lens has the opposite effect—that is, a stronger lens will be required when the distance of the lens from the eye is increased.

In the concave lens, the focal distances being negative, the distance between the object and lens is (algebraically) always less than twice the focal length; consequently, a stronger concave lens is always required when the distance of the lens from the eye is increased. This is apparent from inspection of Fig. 33.

Measurement of Ametropia by the Correcting Lens.—The degree of ametropia may be conveniently measured by the lens required to focus the image of a distant object upon the retina; but since the strength of this lens varies with its distance from the eye, it is necessary to adopt a standard position at which the measuring lens is to be placed. For this purpose it is customary to regard the lens as placed at the anterior focus of the eye. This point, being 15.77 mm. from the first principal point (about 14 mm. from the cornea), corresponds approximately with the position at which spectacle-lenses are worn.

Effect of Lenses upon the Size of Retinal Images.—In general, a lens placed before the eye alters the size of the retinal image; but spectacle-lenses, owing to the fact that they are worn very near the anterior focus of the eye, usually effect only a slight modification in this respect. The effect of placing a convex lens at the anterior focus of the eye is illustrated in Fig. 34, in which A represents the refracting surface of the reduced eye. We have learned that, in estimating the size of images, the interval between principal points may be disregarded; hence, if $A\,F$ and $A\,F'$ represent the anterior and posterior focal distances of the eye, $I\,I_1$ will represent the image of

FIG. 34.



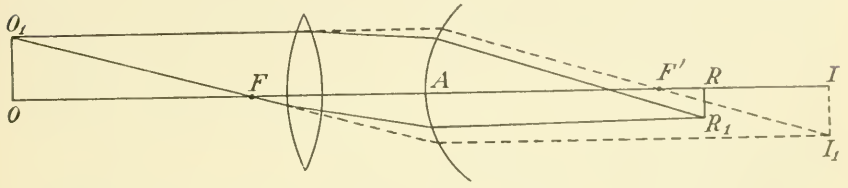
the object $O\,O_1$ in the refraction by the eye alone. If the image $I\,I_1$ lies behind the retina $R\,R_1$, it may be brought forward by a convex lens. When this lens is placed at the anterior focus, as illustrated in Fig. 34, the ray $O_1\,F$, passing through the anterior focus, passes also through the nodal point of the lens; consequently, its direction is unaltered by the lens, and the image $R\,R_1$ on the retina has the same size as $I\,I_1$, formed by the eye without the aid of the lens.

If the lens is placed within the anterior focus, the image is minified, as is apparent from inspection of Fig. 35. It is only when the convex lens is placed without the anterior focus that it exerts a magnifying power upon retinal images.[1]

[1] The algebraic demonstration of the effect upon images of adding a lens in any position may be found in the author's "Handbook of Optics," Chapter VII.

Similarly, it may be proved that a concave lens exerts the opposite effect; that is, a concave lens magnifies or minifies the image according as it is within or without the anterior focus.[1] As in the case of the convex lens, no change in size of the image is produced by a concave lens placed at the anterior focus.[2]

Fig. 35.



In hyperopia distinctness of vision is attained by accommodative action, whereby the focal distances of the eye are shortened and images reduced in size. By the substitution of a convex lens placed at the anterior focus the accommodation is relaxed, the focal distances resume their normal dimensions, and images are proportionately enlarged. When, as is usually the case, the lens is worn without the anterior focus, there is additional enlargement due to the magnifying power of the lens. Even in high hyperopia, however, the difference in size of images without lens-correction and with it is not great. The difference is, nevertheless, appreciable, for it is possible to discern very slight changes in the dimensions of the stimulated retinal area.

Similarly, when convex lenses are used as reading glasses, these being necessitated by failure of accom-

[1] It is thus apparent that the customary practice of illustrating the magnifying power of a convex lens by means of the enlargement of the virtual image, and the minifying power of a concave lens by means of the minification of the virtual image is inaccurate. An actual magnification or minification occurs according as the lens in combination with the eye produces a larger or smaller image than is produced by the eye alone.

[2] This applies only to thin lenses in which the lateral displacement of the nodal ray is inappreciable.

modation, retinal images are slightly larger than when the focal distances are shortened by accommodative action.

In myopia distinct distant vision is impossible without a correcting lens. When the myopia is due to axial elongation (the focal distances being normal), the proper concave lens placed at the anterior focus of the eye will cause images to be sharply defined on the retina without changing the size as formed in front of the retina without the lens; that is, in axial myopia, as in axial hyperopia, the retinal images have the same size as in emmetropia, provided the correcting lens is placed at the anterior focus of the eye.

Near vision is accomplished in myopia either without any accommodation or with less than would be required by an emmetropic eye; hence, in uncorrected myopia images of near objects are slightly larger than in emmetropia. But when the myopia is corrected by a lens, the same amount of accommodation must be exercised as in emmetropia, with a consequent diminution of images. If the lens is worn without the anterior focus of the eye the minification is still more pronounced.

Enlargement of Images Effected by Extraction of the Crystalline Lens.—In aphakia the anterior focal distance (23.14 mm.) is materially greater than that (15.77 mm.) of the schematic eye; consequently, images are proportionately enlarged by extraction of the crystalline lens. However, if the axial length of the eye is normal the image as formed by the aphakic eye will lie far behind the retina, and distinct vision can be obtained only by the aid of a strong convex lens placed in front of the eye. This lens, worn as a spectacle-glass, will be within the anterior focus of the eye in its aphakic condition, and the lens will consequently diminish the size of images, so that they will more nearly correspond to those of the normal eye.

It is in extreme axial elongation (high myopia) that the enlargement resulting from lens-extraction is most noticeable. Thus, if the elongation is so great that the retina coincides with the posterior focus (31 mm. from the cornea) of the aphakic eye, the image of a distant object will, after lens-extraction, be clearly formed on the retina without any correcting lens; each linear dimension of the image as thus formed will be about one and a half times as large as with the concave correcting lens placed at the anterior focus prior to the extraction.

Length of Axis in Ametropia.—Provided it may be assumed without error in any case of hyperopia or myopia that the curvatures, indices, and intervals do not materially differ from those of the schematic eye, the degree of ametropia, as measured by the correcting lens, affords a means of estimating the deficiency in length of the eye in hyperopia or the excess in myopia. In the equation $\frac{1}{f}+\frac{n}{f'}=\frac{1}{F}$ the anterior focal length of the eye is represented by F, the distance of O (the far-point of the eye) from the first principal point is represented by f, and the distance of the retina R from the second principal point by f'; n represents the index of the vitreous.

The excess or deficiency of length may also be directly derived from the equation $l'=\frac{FF'}{l}$, in which l is the distance of the far-point from the anterior focus, and l' is the distance of the retina from the posterior focus.

In the application of this formula to myopia of 10 D., as measured by the correcting lens at the anterior focus, $l = 100$ mm. By substituting for F (15.77) and for F' (21.08) their numerical values, the corresponding value of l' is found to be 3.3 mm.

This is the distance of the retina from the posterior principal focus; or the excess of length for 10 D. of myopia is 3.3 mm.

In hyperopia of 10 D., as measured by the correcting lens, l, being negative, is equal to —100 mm., and by the substitution of this value the corresponding value of l' is found to be —3.3 mm., that is, the deficiency in length for this amount of hyperopia is 3.3 mm.

As thus measured the deficiency in hyperopia is equal to the lengthening in the corresponding degree of myopia, but in order to make an exact comparison both hyperopia and myopia must be measured from the first principal point.[1] The hyperopia which requires a correcting lens of 10 D. is expressed by $\frac{1}{0.0842}$ D., or 11.8 D. when measured from the first principal point, and the myopia which requires a correcting lens of 10 D. is expressed by $\frac{1}{0.1157}$ D., or 8.6 D. when measured from this point; hence, when the ametropia is measured from the first principal point the shortening in hyperopia is less than the lengthening in the corresponding degree of myopia.

Axial Length of the Eye in Relation to the Probable Refractive Condition Resulting from Lens-extraction.—From the equation $\frac{1}{f} + \frac{n}{f'} = \frac{1}{F}$ the power of the correcting lens which will be required in the aphakic condition may be derived, the calculations being based upon the measurements of the schematic eye. For this purpose f and f' represent the conjugate focal distances in the refraction by the aphakic eye, and F represents the anterior focal length of this eye.

[1] It is only in high-grade ametropia, however, that it makes any material difference whether the measurements are made from the anterior focus or the first principal point.

In the application of this formula to an eye which is emmetropic before lens-extraction, the axial length being therefore presumably 23.23 mm., this length (23.23 mm.) represents f', the second conjugate focal distance in the refraction by the aphakic eye; F, the anterior focal length, is in the aphakic eye equal to 23.14 mm., and n (1.337) represents the common index of the aqueous and vitreous. The corresponding value of f (— 69 mm.), derived by making these substitutions, measures the hyperopia of the aphakic eye; for f and f' being conjugate foci, the rays which converge to I (Fig. 32) before entering the eye will be so refracted by the eye as to be focused at its conjugate on the retina. The value of f as thus derived expresses the hyperopia as measured from the anterior surface of the cornea; in order to ascertain the focal length of the corresponding lens, its distance from the cornea must be added to 69 mm. If the lens is placed 14 mm. from the cornea its focal length must be 83 mm., corresponding to a dioptric power of 12 D. Thus, theoretically, when the lens has been extracted from an emmetropic eye, a convex lens of 12 D. is required to overcome the resulting hyperopia.[1]

In other refractive conditions the same equation serves to determine the probable strength of lens which will be required in aphakia, the value of f' being always the axial length corresponding to the degree of ametropia prior to the lens-extraction. This value of f' may be determined by calculation, as already explained,

[1] Since individual eyes differ more or less from the schematic eye in their measurements, it is not to be expected that the lens as practically determined will correspond exactly with that derived from calculation. As a rule, a lens of 10 D. or 11 D. affords best distant vision after lens-extraction from an eye which was emmetropic prior to the formation of cataract. This slight deviation from the mathematical result may be due (as has been suggested) to an almost imperceptible change in form of the eyeball, resulting from the removal of the lens.

or it may be taken from the tabulated record of such calculations.

A condition of practical interest is that in which the eyeball has undergone great elongation, thus producing a high degree of myopia. It is desirable to know whether such an eye will be myopic, emmetropic, or hyperopic after extraction of the lens. The posterior focus of the aphakic eye of normal curvature and index lies 31 mm. behind the anterior surface of the cornea; consequently, if a myopic eye is so elongated that the retina lies at this distance (31 mm.) from the cornea, the eye will be exactly adapted to focus the image of a distant object upon the retina when the crystalline lens is removed from the eye, provided the curvature and index are normal. If, under the same conditions, the axial length is more than 31 mm., the eye will still be myopic after lens-extraction; but when the length is less than this, the aphakic eye will be hyperopic. An axial length of 31 mm. corresponds to myopia slightly in excess of 24 D., as measured by the concave correcting lens placed 14 mm. in front of the cornea. This is the degree of axial myopia, therefore, which an eye must have under average conditions, in order that it shall be emmetropic after extraction of its crystalline lens.

CHAPTER VII.

ASYMMETRICAL REFRACTION.

The curvature of asymmetrical surfaces varies with every variation of meridian, thus differing from that of spherical surfaces, which have the same curvature in all meridians.

The Cylindrical Surface.—The curvature of this surface is greatest in a transverse section—that is, at right angles to the axis of the cylinder—and it is least in the direction of this axis, in which direction there is no curvature. In the first direction the diagrammatic representation of refraction is the same as that for a spherical surface of corresponding curvature; while in the direction of the axis the diagram representing refraction at a plane surface is applicable.[1]

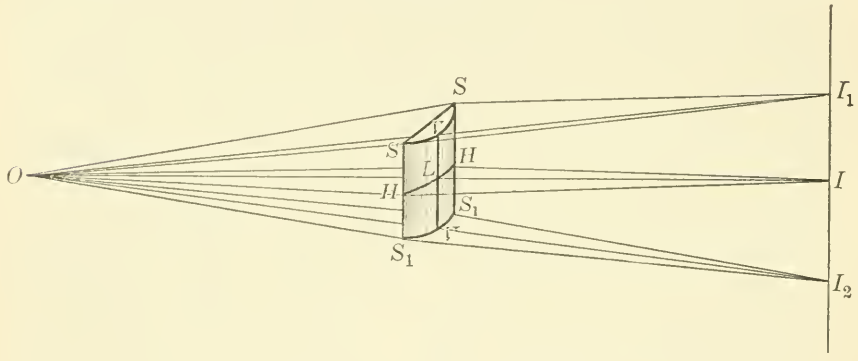
Principal Meridians.—By the aid of the meridians of greatest and of least curvature, it is possible to trace the path of all rays which are refracted at an asymmetrical surface. For this reason these two meridians are called the *principal meridians* of the surface.

Refraction by a Cylindrical Lens.—A cylindrical lens may be formed of an entire cylinder, but usually it consists of a segment, of which one surface is cylindrical and the other plane and parallel to the axis of

[1] One must not, however, fall into the error of supposing that in an intermediate meridian cylindrical refraction is comparable to spherical refraction in this meridian; for in the former, owing to the direction of the normal (which must always lie in the plane of refraction), a ray proceeding from a point and meeting the surface in an intermediate meridian will not lie in a common plane with the optic axis after refraction, and will, consequently, never intersect this axis—that is, in *cylindrical refraction there is no focus in any oblique meridian.*

the cylinder. Refraction by such a lens is illustrated in Fig. 36, in which *H L H* represents an arc lying in the meridian of greatest curvature, and the straight line *V V*, drawn through the summit of curvature, perpendicular to the arc or parallel to the axis of the cylinder, is the *axis of the lens.* The straight line *O I* represents the *optic axis,* which must be distinguished from the axis of the lens. It is convenient to regard the plane of the paper as vertical and the plane *O H I H,* in which the section of greatest curvature lies, as horizontal. With this understanding, it is apparent from the diagram that none of the rays included in

FIG. 36.



Refraction by a cylindrical lens.

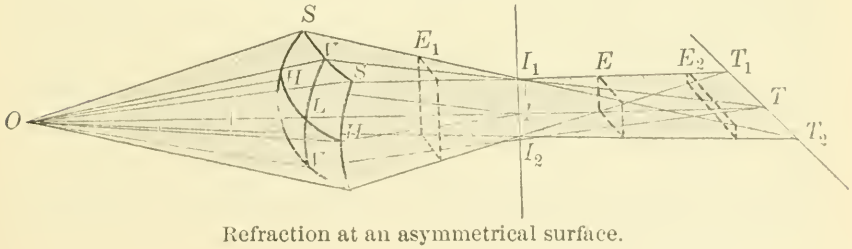
the angle *H O H* (lying in the horizontal plane) will be deviated in the vertical direction, for in this direction these rays are all perpendicular to both surfaces of the lens; but in the horizontal plane they are all (except the optic axis) refracted just as in spherical refraction, and if *I* is conjugate to *O,* they must be focused at *I.* The rays which pass through any other horizontal arc, as *S V S,* are not perpendicular to the surfaces in the vertical direction; but in this direction the two faces of the lens are parallel, and, consequently, the vertical deviation at the first surface is exactly neutralized by

that at the second surface. It is apparent, therefore, that (neglecting the thickness of the lens) $O\,V\,I_1$ must be a straight line, and that all the rays passing through the arc $S\,V\,S$ must be focused at I_1, for these rays undergo the same horizontal refraction as those which pass through the arc $H\,L\,H$. Similarly for every group of rays passing through any horizontal arc there is a corresponding point on the line $I_1\,I_2$, where these rays are focused; hence, every ray which passes through the lens must intersect the line $I_1\,I_2$, drawn through the conjugate I and parallel to the axis of the lens.

When the point O is so far distant that the rays may be regarded as parallel, $I_1\,I_2$ is the (principal) *focal line*, and $L\,I$ is the (principal) *focal length* of the lens.

Toric Surfaces.—In the cylindrical surface the axis $V\,V$ (Fig. 36) is a straight line; the surface may be

FIG. 37.



Refraction at an asymmetrical surface.

regarded as produced by the arc $S\,V\,S$ sliding along the line $V\,V$, the plane of the arc being perpendicular to this line. Let us suppose the line $V\,V$ to be flexible, so that it may itself become the arc of a circle, as in Fig. 37. The surface generated by the arc $S\,V\,S$ is no longer cylindrical; it is a *toric surface*. If the radius of the arc $V\,L\,V$ is the same as that of the arc $H\,L\,H$, the surface is spherical; when the radius of $V\,L\,V$ is infinite this arc becomes a straight line and the surface is cylindrical; the cylinder and the sphere

are each identical, mathematically, with the torus, and any formula which is applicable to the torus must be applicable also to these surfaces.

We have learned that the action of a cylindrical lens is confined to one principal meridian, there being no deviation in the other principal meridian. The only respect in which refraction at a single toric surface differs from that by a cylindrical lens is that in the former the rays undergo deviation in *both* principal meridians. Toric refraction is illustrated in Fig. 37, in which $V\,V$ represents the vertical and $H\,H$ the horizontal curvature; O is the point from which the pencil of light proceeds; I is conjugate to O in the horizontal refraction, and T is conjugate to O in the vertical refraction. Whatever may be the vertical curvature, all the rays must pass through the vertical line $I_1\,I_2$, just as in refraction by the cylindrical lens.

The effect of the vertical curvature is to bend the rays in the vertical meridian—to change the points at which the rays meet the line $I_1\,I_2$; but they must all pass through this line, just as if there were no vertical deviation. Similarly, the rays must all pass through the horizontal line $T_1\,T_2$, which is conjugate to O in the vertical refraction. Hence, in toric refraction all the rays proceeding from a point must pass through two focal lines corresponding to the foci in the two principal meridians.

When the point O is so far distant that I and T become the principal foci in the two principal meridians, $I_1\,I_2$ and $T_1\,T_2$ are the (principal) *focal lines* and $I\,T$ is the (principal) *focal interval*.[1]

If the curvature is the same in the two principal meridians—that is, if the surface is spherical—the two focal lines will intersect and there will be no focal

[1] Also called Sturm's interval, in honor of the first demonstrator of asymmetrical refraction. C. R. de l'Acad. des Sci. de Paris, t. xx. pp. 551, 761, 1238.

interval. If the radius of curvature is infinite in one meridian—that is, if the surface is cylindrical—the focal line corresponding to the meridian of no curvature will lie to the left of *O* so long as the pencil is divergent; when *O* is so far distant that the rays may be regarded as parallel they are all perpendicular to the surface in the meridian of no curvature and undergo no refraction in this meridian; the focus for this meridian is at an infinite distance from the surface. Hence, for rays parallel to the axis (and only for such rays), refraction at a single cylindrical surface is similar to that by a cylindrical lens; other rays meeting a cylindrical surface undergo deviation in both principal meridians.

If a screen is placed at *I* the image of *O* as intercepted by this screen will be the vertical line $I_1 I_2$, and if the screen is at *T* the intercepted image will be the horizontal line $T_1 T_2$. Hence, at the focus of the horizontal meridian the image of a point is a vertical line, and at the focus of the vertical meridian the image is a horizontal line. The length of the line varies with the focal interval, becoming a point when the focal lines intersect. In any other position of the screen the image varies with the form of aperture through which the rays pass into the refracting medium. If, as in the illustration, this is square, the image as projected on a screen at E_1 will evidently be a broad line or rectangle, having its greatest dimension vertical.

The vertical dimension diminishes, and at a certain point, *E*, after the rays have passed their horizontal intersections, the image will be square. Beyond this position the greater dimension of the image will be in the horizontal direction. The vertical dimension continues to diminish until it vanishes and the image becomes a line at *T*; after the crossing of the rays here the vertical dimension again increases, always remaining less than the horizontal dimension.

If, as is usually the case, the opening through which the pencil passes is circular (as the pupil of the eye), we have only to cut off the rays passing near the corners to obtain the image in the various positions of the screen. At E_1 the image will be an oval, having its long axis vertical; at I, as before, it will be a vertical line; at E it will be a circle, and so on. When the image of a point is a circle, the latter is called the *circle of least confusion*.[1]

The image of a vertical line passing through O will, as projected upon a screen at I, be an intensified line, for each point of the line will have as its image a vertical line, such as $I_1 I_2$; but if the screen is placed at T, each point of the line will have as its image a short horizontal line, as $T_1 T_2$, and the aggregation of all these lines will make a broad and indistinct line as the image of the vertical line. At any other point the image of the vertical line will be made of a superposition of ellipses or circles.

The image of a horizontal line passing through O will be the reverse of that of the vertical line; that is, the image will be a broad and indistinct line at I and an intensified line at T.

The image of a line lying in an oblique meridian will be blurred in all positions of the screen.

It thus appears that the image of a line lying in one principal meridian will be distinct at the focus of the other principal meridian, and most indistinct at the focus of the meridian in which it lies.

Toric Lenses.—These may be biconvex, biconcave, plano-convex or plano-concave or concavo-convex—that is, they may have a toric curvature ground upon one face, while the other face may be plane or spherically convex or concave.

[1] For a method of determining the position of this circle consult Hess, in Archiv. für Ophth., vol. xlii., No. 2, p. 97.

The toric lens is considered desirable chiefly because it affords a means of replacing a plano-cylinder or a double convex sphero-cylinder by a periscopic lens. The toric form is also advantageous in certain cases of high myopia or high hyperopia (as after cataract-extraction) complicated with astigmatism.

Owing to the difficulty of grinding, the toric curvature is usually made only by the large manufacturing companies; but opticians who are provided with spherical surface grinding machinery generally keep in stock an assortment of plano-curved toric lenses, on the plane surface of which may be added any desired spherical curvature. These plano-toric lenses are usually made on a curve of either 3 D. or 6 D.; that is, the toric curvature is equal to a spherical lens of 3 D. or of 6 D. combined with the appropriate cylinder. Hence, if a +2 D. cylinder were called for in the periscopic (toric) form, the optician would select a plano-toric lens having a convexity of 3 D. in one principal meridian (or of 6 D. if a greater periscopic effect is required) and of 5 D. (or of 8 D. if the 6 D. curvature is selected) in the other principal meridian. He would then grind on the plane surface a concavity of 3 D. (or of 6 D. if the 6 D. curvature is selected), thus making the refractive power of the lens identical with that of a cylinder of +2 D., and yet giving it the periscopic form. Similarly, by grinding a suitable spherical concavity a convex sphero-cylindrical lens may be replaced by a toric periscopic lens.

Instead of strong concave sphero-cylinders, such as are required in high myopia with astigmatism, a plano-concave toric lens may be adapted by grinding a suitable spherical concavity on the plane surface; by thus dividing the strong spherical concavity between the two surfaces a lighter lens is possible than in the sphero-cylindrical form. Similarly, the strong convex sphero-cylinders required after cataract-extraction may

be advantageously replaced by the double convex sphero-toric curvature. It is possible, also, by increasing the spherical element on the toric surface, to make cataract lenses periscopic, but the great weight of such lenses counterbalances the advantages of the periscopic form.

Bicylindrical Lenses.—1. *The combination of two cylindrical lenses whose axes are parallel* differs in nowise from the combination of two spherical lenses; the combined lenses are equivalent to a single lens whose refracting power is equal to the sum of the powers of the two lenses.

2. *The combination of two cylindrical lenses whose axes are at right angles* is equivalent to a toric lens. If, for instance, the axis of one lens is vertical and that of the other is horizontal, the first lens refracts the rays in the horizontal and the second refracts them in the vertical meridian, precisely as they are refracted in the two principal meridians of the toric lens.

If it is desirable to make a bicylindrical lens on a single plate of glass, one curvature must be ground on each face of the glass, so that all the rays, after receiving the refractive effect of the first curvature, may also receive that of the second curvature. If we wish to grind both curvatures upon one surface we must bear in mind that the second curvature must be superposed upon the first without destroying it; we must, *in effect*, bend the axis of the first cylinder into the curvature of the second cylinder, and we see that in so doing we convert the surface into a torus.

If both cylinders have the same curvature the equivalent toric curvature becomes spherical, and the combined effect of *two equal cylindrical lenses* whose axes are at right angles is identical with that of a *spherical lens having the same radius and index.*

Since two unequal cylindrical lenses, combined at right angles to each other, may be regarded as two

equal lenses so combined with the addition of another cylindrical lens, it follows that such a combination is equivalent in effect to a spherical lens combined with a cylindrical lens. Thus the refractive effect is identical whether the two curvatures are ground as a *toric*, a *bicylindrical*, or a *sphero-cylindrical lens.*

3. *Two cylindrical lenses may be combined, having their axes inclined at an oblique angle.* In this case the two axes of the lenses do not indicate the directions of the principal planes or meridians of refraction in the combination; for the second lens, not being at right angles to the first, deviates the rays out of the plane of the axis of the first lens, and *vice versa.* One would, however, naturally suppose that there must be in such a combination a certain meridian in which the effect of the combined refractions is greatest, and at right angles to this another in which the effect is least. It can, in fact, be readily demonstrated that this is so whatever may be the angle of inclination of the axes; that *any two cylindrical lenses* in combination are equivalent to two other cylindrical lenses *at right angles*, or to the equivalent of this—a *sphero-cylindrical* or *toric* lens.[1]

Perhaps more convincing to the student than the mathematical demonstration (which is somewhat complicated) is practical experiment with the trial lenses. Selecting any two cylindrical lenses from the case of trial lenses, and placing them together at any angle, we view through the lenses (which are held before the eye) two straight lines at right angles to each other, as the edges of a test-card. These lines will, in general, appear to be twisted out of their proper relations; but by rotating the combined lenses a certain position can always be found in which the two lines appear (as they are in reality) at right angles to each other. In

[1] Handbook of Optics (author's), Chapter X.

this case the two lines viewed mark the directions of the principal meridians, and the combination is equivalent to a certain curvature in each of these two meridians; that is, it is equivalent to two cylindrical lenses at right angles, or to a toric or sphero-cylindrical lens. Having ascertained the direction of the principal meridians, the nearest equivalent which is to be found in the trial case is easily obtained by neutralization in first one and then the other of these meridians.

Oblique Refraction.—Our attention has hitherto been confined to direct refraction, in which the axis or central ray of the pencil of light meets the refracting surfaces perpendicularly. Strictly speaking, there can be only one point of an object from which a direct pencil can proceed; this is the point of intersection of the optic axis and the object. All other parts of the object give rise to *indirect* or *oblique* pencils; but when the object is small as compared with its distance from the refracting system, and so situated that its central point lies on the optic axis, the formula which serves to determine conjugate foci for direct pencils serves also for the indirect pencils.

In refraction by the eye the obliquity of pencils may be disregarded, because images falling upon the retina at a distance from the optic axis do not excite a distinct impression in the mind; it is only with such pencils as may be regarded as direct that the process of distinct vision is concerned. But when vision is accomplished with the aid of a lens, the pencils which enter the eye are previously obliquely refracted by the lens if this is placed in a tilted position before the eye. The effect of this obliquity is that which results from spherical aberration. Refraction at a spherical surface increases with the obliquity of the incident rays; hence the refractive power of a lens must be greater when it is tilted so that the rays meet it obliquely than when the refraction may be regarded as direct.

Furthermore, it is apparent that when a lens is tilted it presents its greatest obliquity in the meridian in which the tilting takes place, while the meridian at right angles to this is that of least obliquity; hence, tilting a lens in the vertical meridian increases its refractive power in both vertical and horizontal meridians, but more so in the former. Thus, if there is a common focal distance for all rays in the vertical meridian, and another common focal distance for all rays in the horizontal meridian, oblique refraction is similar to that which occurs at an asymmetrical surface. Although mathematical demonstration shows that this is only approximately true, yet practically, for small pencils, oblique refraction may be classed with such as occurs at toric and cylindrical surfaces.[1]

In a cylindrical lens the refracting power in the direction of the axis is zero, and it must remain so when the lens is tilted. Tilting a cylindrical lens, therefore, increases its power in its refracting meridian; more so when the tilting is in this meridian.

The asymmetrical effect of tilting lenses has an important bearing in the combination of weak cylindrical with strong spherical lenses. A slight amount of tilting, as is almost unavoidable in near work, may either entirely neutralize the cylindrical effect or increase it beyond what is desired.

The following table shows the rate of increase, as computed by Dr. John Green, of St. Louis, when a lens is tilted in the vertical meridian:[2]

Degrees.	*Vertical.*	*Horizontal.*
0	1.000	1.000
5	1.010	1.002
10	1.042	1.010
15	1.097	1.023
20	1.179	1.041
25	1.297	1.166
45	2.464	1.232

[1] Handbook of Optics (author's), Chapter XI.

[2] Trans. Am. Ophth. Soc., 1890.

Thus a spherical lens of 4 D. tilted 15 degrees in the vertical meridian would be equivalent in this meridian to an untilted lens of 4.388 D., and in the horizontal meridian it would be equivalent to one of 4.092 D., the astigmatism acquired by the tilting being 0.296 D.

Prismatic Refraction.—In the passage of light through a prism there is no deviation in the direction of the apex line of the prism, for in this direction the two faces of the prism are parallel; but in the principal plane of the prism the rays are all deviated away from the apex.[1] If all the rays undergo the same amount of deviation, the relative divergence of these rays will be unaffected by the prism—that is, the prism has in this case no power of altering the focal length of pencils. This condition exists for parallel rays and approximately for very small pencils passing through the prism near the position of minimum deviation; but other pencils are altered in length in the meridian of refraction (the principal plane of the prism), and the more so according as they are the more removed from the position of minimum deviation (p. 38). Hence, prismatic refraction is, in general, asymmetrical, the focal interval increasing as the pencils depart from the position of minimum deviation.

ASTIGMATISM.

Since in asymmetrical refraction rays proceeding from a point will never be united in a focus at another point, the resulting condition is called *astigmatism;* but since the image of a point can always be determined from the formula for refraction, the astigma-

[1] It is assumed that all the rays lie in or very near the principal plane. Rays which meet the prism obliquely (not in the principal plane) undergo greater deviation than those which lie in this plane. (Author's Handbook of Optics, Appendix II.)

tism is said to be *regular*, in contradistinction to *irregular* astigmatism, which arises from irregularity or unevenness of surface, or to heterogeneity of refractive index. Our attention is here confined to the study of regular astigmatism which is always indicated by the term astigmatism unless otherwise stated.

Astigmatism of the eye may be due to asymmetrical curvature of the cornea, or to asymmetrical curvature or oblique position of the crystalline lens. Evidently both defects may coexist in the same eye, thus producing both corneal and lenticular astigmatism. When the principal meridians of the corneal and lenticular refractions are identical, the total astigmatism is equal to the lenticular astigmatism added to (or subtracted from) that of the cornea; but when the principal meridians of the lens are obliquely inclined to those of the cornea, the principal meridians of the total astigmatism do not coincide with those of either cornea or lens. The problem is similar to that for the combination of two cylindrical lenses obliquely inclined; that is, the total astigmatism is equivalent to that which would be produced by a certain toric surface.

Correction of Astigmatism.—Astigmatism, whether corneal or lenticular, or both, may always be overcome by means of a cylindrical lens placed before the eye. For instance, if the eye is emmetropic in the horizontal meridian (if the horizontal focus lies on the retina), and myopic in the vertical meridian (the vertical focus lying in front of the retina), a concave cylindrical lens having its axis horizontal, and having such power that in the refraction by the lens LI is conjugate to LO (Fig. 33), will carry the vertical focus back to the retina without changing the horizontal focus; hence, with the aid of this lens the rays will be focused on the retina.

When the eye is ametropic in both meridians a suitable spherical lens may be added to the cylindrical

lens that equalizes the refraction in the two principal meridians; or, instead of this combination, a toric lens may be used having such curvature as will bring the focus upon the retina in both principal meridians.

Distortion of Images in Astigmatism.—In investigating the form of retinal images in astigmatic eyes there are to be considered: (1) The blurred image as it is formed on the retina without the correcting lens, and (2) the focused image as formed with the aid of the lens.

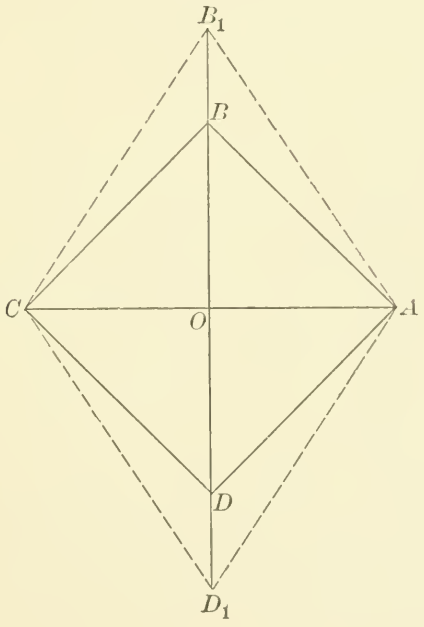
1. Since the linear dimensions of the image may be regarded as proportional to the anterior focal distance, and since this distance is greater according as the curvature is less, it follows that the image as formed in the meridian of least curvature must be greater than that formed in the meridian of greatest curvature. But the retina cannot be in position to receive the focused image in both meridians, and the diffusion of light on the retina in the unfocused meridian tends to enlarge images in this direction. This enlargement must vary with the degree of diffusion (depending upon the size of the pupil) and with the relation of this diffusion to the magnification or minification of the focused image; but ordinarily in uncorrected astigmatism the image is too large in the unfocused meridian, whether this is hyperopic or myopic.

2. When astigmatism is corrected by a lens placed at the anterior focus the image will be brought to a focus on the retina; but the size of the image in the corrected meridian will remain the same as it would be formed without the lens if the retina were in position to receive it at the focus; that is, the image in corrected astigmatism is proportionately too large in the hyperopic meridian and too small in the myopic meridian. If the correcting lens is without the anterior focus the distortion will be further increased by the magnifying or minifying power of the lens. If the

lens could be worn in contact with the cornea the curvature (if the astigmatism is due to asymmetrical curvature of the cornea) would be equalized, and images would be correct in their proportions.

Owing to the disproportion of the image in astigmatism, all lines which are not parallel or perpendicular to the principal meridians must undergo an angular distortion. This is illustrated in Fig. 38: $O\,A$ and

FIG. 38.

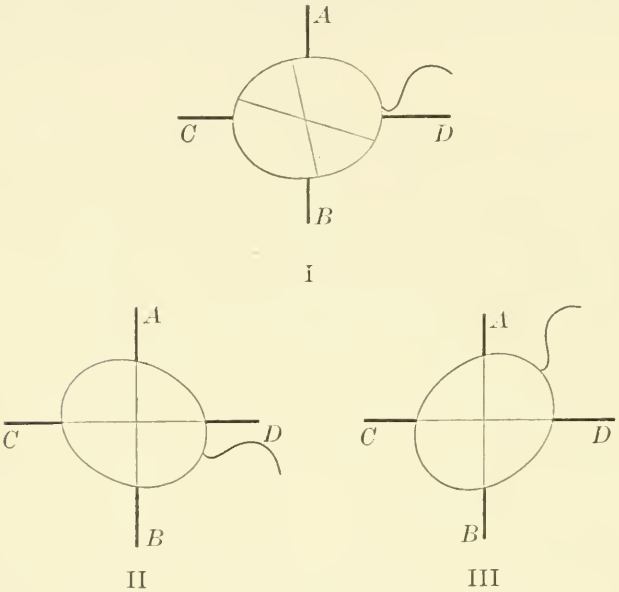


$O\,B$ indicate the directions of the principal meridians, $O\,B$ being that in which the image appears too large. The image of a square whose sides are obliquely inclined to the principal meridians would not be the square $A\,B\,C\,D$ but the oblique figure $A\,B_1\,C\,D_1$, for there is an undue magnification in the direction $O\,B$, so that $B_1\,D_1$ is a longer line than $A\,C$. Hence, the oblique line which would normally appear as $A\,B$

appears in the distorted image as $A B_1$, which makes a greater angle with $A O$ than $A B$ does.

The degree of astigmatism in the eye is slight as compared with the total refraction, and, consequently, the two focal lines are very near each other; hence,

FIG. 39.



I II III

Distortion produced by a cylinder. Determination of the axis of a cylinder. A right-angled cross, $A\ B\ C\ D$, is seen through a glass containing a cylinder. If (I) the axis of the cylinder does not coincide with either $A\ B$ or $C\ D$ the cross will appear twisted, so that the arms no longer make a right angle. The cross, however, is not displaced as a whole either to one side or the other. If now the glass is rotated until the axis of the cylinder coincides with one arm of the cross—*e. g.*, $A\ B$ (II)—the cross will appear right-angled and unbroken. The same thing will happen if the glass is rotated 90° more (III), so that the axis of the cylinder coincides with $C\ D$. (Posey and Wright.)

the actual distortion either with or without correction is not great.

Determination of the Axis of a Cylindrical Lens. —When a cylindrical lens is placed before the eye at a greater distance than that at which spectacles are worn, while a distant object is viewed through the

lens, the distortion becomes very great.[1] This property is used for the ready determination of the direction of the axis of a cylindrical lens. To find the position of the axis we hold the lens before the eye and look through it at a straight line across the room, as the edge of a test-card, rotating the lens in its own plane until we reach that position in which there is no break in the line, as seen through the lens and beyond its border (Fig. 39). The axis is then either parallel or perpendicular to the line. If the length of the line is unaffected by the lens it lies in the direction of the axis, but if it is magnified or minified in length it lies at right angles to the axis; or if a movement of the lens in the direction of the line does not affect the apparent position of objects the line lies in the direction of the axis, but if such movement produces apparent displacement the line is at right angles to the axis. If the displacement is in the opposite direction to that of the lens, or if an oblique line appears to make a greater angle with the axis than really exists, the lens is convex; if the displacement is in the direction of motion of the lens, or if an oblique line appears to make a less angle with the axis than really exists, the lens is concave.

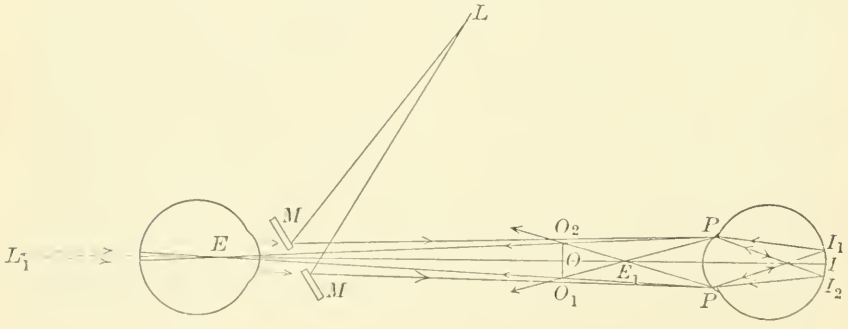
[1] For explanation of the phenomenon produced by holding a convex cylindrical lens beyond its focal length, see "Handbook of Optics" (author's), Chapter IX.

CHAPTER VIII.

OPTICAL PRINCIPLES OF OPHTHALMOSCOPY, SKIASCOPY, AND KERATOMETRY.

In Fig. 40 *P P* represents the pupil of a myopic eye in which *O* and *I* (or O_1 and I_1 and O_2 and I_2) are conjugate points; *M M* represents a plane mirror by which light is reflected from the flame, *L*, into the eye, *P P*. The light will enter the eye as if diverging from a point, L_1, as far behind the mirror as *L* is in

Fig. 40.



Illustrating the path of the reflected and refracted rays in indirect ophthalmoscopy and in skiascopy. The rays emerging from the eye (*P P*) undergoing examination are rendered convergent by inherent myopia of this eye or by a convex lens placed in front of the eye. (This diagram should be carefully studied in connection with skiascopy.)

front of it; and since this point is farther than *O* from the eye, the rays will cross in front of the retina and form on the latter a diffusion image, $I_1 I_2$. Some of the light from the illuminated area $I_1 I_2$ undergoes irregular reflection and passes out of the eye. Of these

reflected rays, all which proceed from I, must intersect at its conjugate, O, all which proceed from I_1 intersect at O_1, and all which proceed from I_2 intersect at O_2; hence, at O_1 O_2 there is formed a real and inverted (aërial) image of the illuminated portion of the fundus.

If the flame were so arranged that the light entered the eye as if diverging from O, conjugate to the retina, there would be no diffusion, but only a focused image of the flame, and if the latter were very small the image would be reduced to a mere point on the retina; but if the rays should diverge from a point within the conjugate O they would reach the retina before their union in a focus, and, as before, a diffusion image would be formed. *Hence, the area of illumination on the retina is greater as the point of origin of the light is the more remote from the conjugate to the retina.*

It is only in myopic eyes that a real image of the illuminated area will be formed, for in emmetropia the anterior conjugate to the retina is at an infinite distance from the eye, the emergent rays being parallel, and in hyperopia the emergent rays are divergent, appearing to proceed from a virtual focus behind the eye (illustrated in Fig. 32 by reversing the course of the rays). But the emergent rays in emmetropia and hyperopia may be united in a real aërial image in front of the eye by means of a convex lens placed before the eye, the position at which the image is formed varying with the strength of lens employed. Similarly, the aërial image may be brought nearer to a myopic eye by the addition of a convex lens.

The relative size of the image and illuminated area depends upon the respective distances of the image and retina from the nodal point. Thus in myopia of 10 D. the image is situated approximately 107 mm. from the nodal point, and the retina is about 19 mm. from this point; hence, the magnification of the image is about $5\frac{1}{2}$ diameters. The magnification diminishes with the

increase of myopia or with the addition of a convex lens placed near the eye.[1]

Helmholtz discovered (1851) the principles underlying the formation of these images: he not only explained why they are not ordinarily visible, but he also invented a simple device (the ophthalmoscope) by means of which the details of the fundus can be minutely inspected. The *ophthalmoscope* (Figs. 60 and 61), in its simplest form, consists of a plane or concave mirror having at its centre a small circular opening, through which rays of light emerging from an illuminated eye are permitted to pass into the eye of an observer. There must also be attached to the mirror a series of lenses to facilitate the focusing of the fundus-image. An arrangement of this kind is necessary to enable the observer to place his eye in the path of the returning rays, except in the high grades of hyperopia or myopia, in which conditions the fundus-image may be seen in a darkened room if the observer places his head close beside a lamp, or other suitable source of illumination, and looks in the direction of the eye under examination: the greater the degree of ametropia the more easily will this be accomplished, because of the greater difference between the paths of the entering and the emerging pencils.

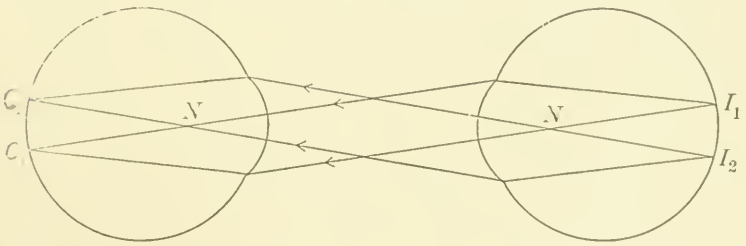
Indirect Method.—This consists in the examination of the aërial image formed in front of an eye, whether as the result of inherent myopia or as produced with the aid of a convex lens. The aid of a lens must be invoked in all but the highest grades of myopia, since otherwise the aërial image would be so far in front of the eye that, although highly magnified, only a very small portion of the fundus would be visible. The power of the convex lens may be varied

[1] It must be borne in mind that when a lens is placed before the eye the nodal point is not the nodal point of the eye, but the nodal point of the compound system formed by the eye and lens together.

to suit circumstances: usually it is found most convenient to employ a lens of 13 D., producing in emmetropia a magnification of about 4 diameters; in myopia a weaker lens may frequently be substituted with advantage. The observer looking through the sight-hole of the illuminating mirror may most readily examine the aërial image when his eye is about ¼ metre beyond it; if it should be burdensome to focus the rays diverging from this image, accommodative action may be replaced by a convex lens (4 D.) which is attached to the instrument.

Direct Method.—The aim in this method is to approach the eye under examination as closely as is compatible with good illumination, the convex lens

Fig. 41.



Illustrating the path of the refracted rays in direct ophthalmoscopy.

used in the indirect method being in this method replaced by the eye of the examiner, so that the real inverted image is formed on the latter's retina, as is illustrated in Fig. 41. In this illustration both examined and examining eyes are emmetropic; all the rays which emerge from any point of the illuminated area are parallel, and some of these rays from each of the points of this area will enter the observer's eye and will be focused on his retina without exercise of accommodation. If the examined eye is myopic the emergent rays are convergent (not having yet intersected in the aërial image), and in order that they may be focused upon the retina of an emmetropic observer a

concave lens (which is attached to the ophthalmoscope) must be placed before the observer's eye so as to render the rays parallel. If the examined eye is hyperopic the emergent rays will be divergent, and can be focused on the retina of an emmetropic observer only by exercise of accommodation or by the aid of a convex lens.

Since all objects are inverted with respect to the retinal image, it is apparent that in this method the observer will see the fundus-image of the examined eye in its natural or erect position. The fundus-image will also be magnified, since any refracting system which enables us to see clearly the fundus at such short range must produce magnification as compared with the size as it would appear when seen without the refractive influence of the examined eye. From Fig. 41 it is apparent that when both eyes are emmetropic the retinal image as formed in the observer's eye has exactly the same size as the fundus-area under examination. Since the relative size of object and image is dependent upon their respective distances from the nodal point of the eye, it is apparent that an object placed 25 cm. (10 inches) from the eye must have a diameter 16 times as great as that of its image on the retina, this being the ratio of 257 : 16 (approximately);[1] hence in emmetropia each dimension of the fundus-image appears about 16 times as large as it would if surrounded by air and placed at a distance of 25 cm. from the examining eye.[2] In hyperopia the magnification is somewhat less, diminishing with the increase of distance between the two eyes, and in myopia the magnification is greater and increases with the distance between the two eyes.[3]

[1] The nodal point, being about 7 mm. from the cornea, must in this instance lie 257 mm. from the object and 16 mm. from the retina.

[2] This is the distance at which a small object is usually examined by an emmetrope, and, consequently, it is taken as the standard of comparison in estimating magnifying power.

[3] Handbook of Optics (author's), p. 194.

SKIASCOPY.

In the two preceding methods it is the purpose of the examiner to see clearly the details of the fundus—in the one case by means of an inverted aërial image, and in the other by focusing the emergent rays directly upon his own retina. In the method now to be considered the object of the observer is not to see distinctly the details of the fundus-image, but to place his eye as nearly as possible in the position at which the aërial image of the examined eye would be formed, and to determine from this position the degree of myopia of the examined eye, whether natural or produced by the addition of a convex lens.

Point of Reversal.—We have learned that the myopia of an eye is measured by the distance at which an object must be situated in order that it shall be focused on the retina without accommodation; that is, by the distance between the eye and its far-point. Since the retina and the far-point of an eye are conjugate, it is apparent that the place of formation of the aërial image coincides with the far-point; hence the position of the aërial image determines the degree of myopia. Since the emergent rays coming from any point of the fundus intersect in the aërial image, their relative position is reversed at this point, which, consequently, is called the point of reversal, this being identical with the far-point.

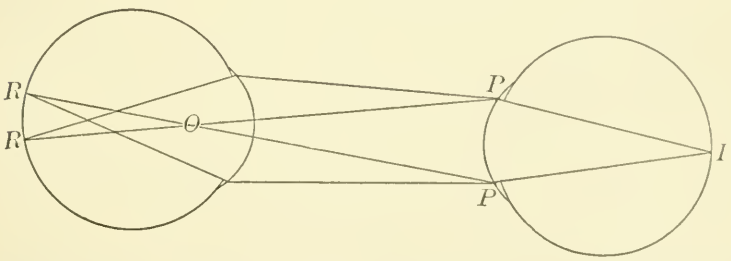
Reversal of Movement.—If by tilting the mirror the illuminated area $I_1 I_2$ (Fig. 40) is shifted downward it is apparent that the aërial image $O_1 O_2$ will move upward, and if the examiner is farther than this image from the examined eye he will observe this movement; but if he is nearer the eye than the point of reversal—that is, if he is using the direct method—the virtual image from which the rays appear to proceed will move

in the same direction as the light on the retina. This, then, is the first aim of the examiner: to determine whether he is without or within the point of reversal by watching the movement of the light-area in the pupil of the eye under examination, while he varies the position of the light on the retina by slight movements of the illuminating mirror. When the examiner is well without or within the point of reversal it is easy for him to see the fundus-image change its position as he varies the light-area on the retina; but when he is very near the point of reversal no details of the fundus can be seen, and he must decide as to the direction of movement by observing the variations of light and shade in the pupil.

Variation of Magnification.—It was stated, in speaking of direct ophthalmoscopy, that the magnification increases in myopia as the distance between the two eyes increases. This increase of magnification continues until the examiner's nodal point coincides with the point of reversal of the examined eye, at which point the magnification is infinite. Beyond this point the aërial image will be seen, and the apparent size of this will diminish as the distance of the examiner's eye from it increases. The effect of change in the observer's position is illustrated in Figs. 40 and 42. When the examining eye is at E, as illustrated in Fig. 40, the apparent size of the aërial image $O_1 O_2$ exactly coincides with the apparent size of the pupil ($P P$) of the examined eye; hence if $I_1 I_2$ is the illuminated area on the fundus, the examiner will see the image $O_1 O_2$ completely filling the pupil $P P$. If no attempt is made to focus the rays diverging from the aërial image, either by accommodation or by the aid of a convex lens, but if, instead, the examiner adapts his eye for the pupil of the examined eye, he will see only the red reflex filling the pupillary space. If now he removes to a greater distance while the illuminated area $I_1 I_2$

remains unchanged, the image $O_1 O_2$ will appear smaller than the pupillary space, and the central red reflex will be surrounded by a circular band which remains in shadow. If, on the other hand, he approaches the aërial image its apparent size increases, becoming finally many times larger than the apparent size of the pupil; or as the examiner approaches the image the less is the portion of this image which lies in the field of view at one time, and the greater is the magnification of this visible portion. When the examiner's nodal point is at *O* (Figs. 40 and 42) a single point, *I*, on

FIG. 42.



Illustrating the illumination of the pupil (*PP*) when the nodal point of the examiner's eye is at *O*, which is conjugate to *I*. The diffusion image (*R R*) of *I* as formed on the examiner's retina exactly coincides with the image (*R R*) of the pupillary border (*P P*).

the retina suffices to illuminate the entire pupil *P P*, whereas when the examiner was at *E* (Fig. 40) the whole area $I_1 I_2$ had to be illuminated in order that the reflex should fill the entire pupil; hence, when the examiner is near the point of reversal he receives light from a very small portion of the fundus, and this light is not focused on his retina, but diffused over an area corresponding to his retinal image of the pupillary border of the examined eye. It is apparent, therefore, that in this position no details of the fundus-image can be seen. As the examiner passes within the point of reversal the magnification diminishes, and when his eye is at E_1 (Fig. 40) the area $I_1 I_2$ must be illuminated in

order that the red reflex may fill the pupil, just as when his eye was at E. If he approaches still nearer, while the illuminated area $I_1 I_2$ remains unchanged, the central red reflex will be surrounded by a dark border of unilluminated pupil.[1]

Movement of the Shadow Across the Pupil.—Let us again suppose the examiner's eye to be placed at E (Fig. 40) and $I_1 I_2$ to be the illuminated fundus-area; the entire pupil glows with the red reflex. If now the light-area is shifted downward so that the upper portion $I I_1$ is no longer illuminated, it is clear that the corresponding area, $O O_1$, will not be illuminated—the lower portion of the pupillary space will be in shadow. As the area of illumination continues to move downward the shadow moves upward, and when the light has been shifted so far downward as to leave the entire area $I_1 I_2$ in darkness, the image will have moved so far upward as to be out of the examiner's line of vision; that is, it will be above the pupil of the examined eye, and the latter will appear to him to be unilluminated. The rapidity with which the shadow moves across the pupil varies with the examiner's position with reference to the point of reversal, being the more rapid as he approaches this point. When he is at this point the entire pupil glows as long as the single point I is illuminated, and when the light-area passes below I, darkness quickly covers the pupil. When he is near, but not at the point of reversal, the examiner will see the shadow move very rapidly across the pupil as the light-area is shifted by rotating the mirror.

When the examiner passes within the point of reversal the shadow again begins to move more slowly, but now, as the light-area moves downward, the upper

[1] We do not meet with this condition in ophthalmoscopy because as the examiner approaches the examined eye the light-area on the retina increases and the entire pupil is illuminated.

border of the pupil appears in shadow, and the border-line between light and shade moves downward; that is, in the same direction as the light-area. In emmetropia and in hyperopia the examiner is always within the point of reversal, and, consequently, in these conditions the shadow always moves in the same direction as the light-area unless the eye is rendered myopic by the addition of a convex lens.

Form of the Shadow.—The light-area on the retina will be circular, or approximately so, since the light is reflected by a circular mirror and enters the eye through the circular aperture of the pupil; hence the shadow-edge must correspond more or less closely to the arc of a circle. The curvature of this arc will vary with the portion of the outline of the light-area which falls into the line of vision; that is, the edge will be more curved as the magnification is less, or according as the examiner is the more remote from the point of reversal. As he approaches this point the curvature diminishes, and the swiftly moving border-line appears almost as a straight line, attaining the latter form when the point of reversal is actually reached, although the movement is then too rapid for discrimination.

Illumination of the Retina.—If this is effected by a plane mirror the apparent source of light is as far behind the mirror as the flame is in front of it; but if a concave mirror is used an aërial image of the flame will be formed in front of the mirror, and this will be the apparent source of illumination. When the plane mirror is used the light-area on the retina will move in the same direction as the rotation of the mirror, but with the concave mirror the light-area must move in the opposite direction to the movement of the aërial image furnishing the illumination; that is, the light-area moves in the opposite direction to the rotation of the mirror.

It has hitherto been assumed that the illumination on the retina remained fixed in all the various positions of the examiner; but when he changes his position he also changes the position of the mirror, and with it the apparent point of origin of the illuminating rays. We have learned (p. 111) that under the same illumination the light-area on the fundus is more diffused according as the point of origin of the rays is the more remote from the point of reversal; hence, in order to have a bright, well-focused light-area, giving a sharp contrast between light and shadow, it is advantageous that the light should be so arranged that as the examiner approaches the point of reversal the apparent source of illumination should also be near this point. This is best accomplished with a plane mirror and a movable flame (having an opaque chimney in which is a small circular opening), such that it can be brought very near the mirror.[1] The apparent source of illumination is then a short distance behind the mirror. If a concave mirror is used the aërial image approaches the mirror according as the flame is more remote from it; hence, in this method the flame should be placed as far as possible from the mirror.

Brightness of the Reflex in the Pupil. —Although the light on the retina is most concentrated when the examiner and the apparent source of illumination are near the point of reversal, yet, owing to the great magnification in this position, the light which enters the examiner's eye all comes from a small portion of the retina, and from a portion lying near the axis where illumination is less intense because of the sight-hole in the mirror; hence, the brilliancy is not so great as it would be if these counterbalancing features were absent, but yet it is perceptibly greater than when the examiner is remote from the point of reversal.

[1] A small electric lamp may be directly attached to the instrument.

Two Points of Reversal in Astigmatism. — In regular astigmatism there is a separate point of reversal for each of the principal meridians, and when the examiner is at this point for one meridian he will be remote from that for the other meridian, the more so according as the astigmatism is greater. The rapidity of the shadow movement will, therefore, be different in the two principal meridians. If this movement is such as to indicate that the examiner is at the point of reversal in one meridian there will be a well-defined shadow movement in the other meridian, and this will be with or against the light-motion according as the second meridian is less or more myopic than the first meridian.

Rectilinear Shadow in Astigmatism.—The appearance of a band of light bordered by a straight shadow-edge is indicative of astigmatism. This appearance is produced when the examiner is at or very near the point of reversal for one principal meridian, in which case the magnification is infinite for this meridian, but is less in the other meridian according as the astigmatism is greater. Hence, in the former meridian the circular or oval light-area will be so magnified without a corresponding magnification in the latter meridian that it will appear in the pupil as a band of light extending entirely across the pupil in the more magnified meridian. The magnification being infinite in this direction, the lines which separate the light from the shadow must appear as straight lines.

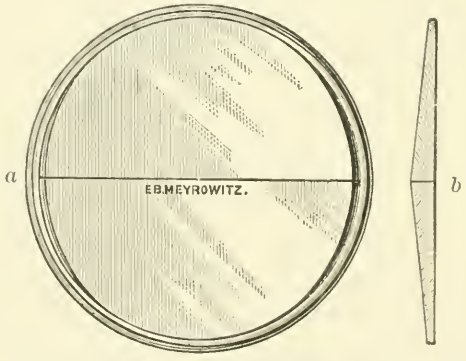
The border-line is emphasized when the light is most sharply focused in the meridian in which the shadow appears; this is accomplished by removing the apparent source of illumination away from the point of reversal at which the examiner's eye is placed. If the plane mirror is used, the flame should be removed as far as possible from the mirror, but only so for the purpose of determining the direction which the shadow-line

occupies, and thereby the direction of one of the principal meridians of the astigmatism. This change in position of the flame is, however, unnecessary except in low grades of astigmatism; when the latter is marked the direction of the shadow-line can readily be determined without this precaution.[1]

KERATOMETRY.

Keratometry or ophthalmometry (as it is more frequently, but less appropriately, called) consists in the measurement of the curvature of the anterior surface of the cornea. The posterior surface of the cornea and the two surfaces of the crystalline lens can also be

FIG. 43.



Maddox double prism. *a*. Front view. *b*. Sectional view.

measured in the living eye, but for clinical purposes measurements of curvature are confined to the anterior surface of the cornea.

Here, again, we are indebted to Helmholtz, who (1854) invented the first ophthalmometer.[2] If one

[1] The student who is unfamiliar with the practical application of these phenomena should read in this connection the description of the manner of conducting the skiascopic examination, as given in Chapter XI.

[2] Helmholtz's instrument was adapted for measuring the curvature of the lens as well as that of the cornea.

places a Maddox double prism (Fig. 43) before one eye so that the apex of the prism bisects the pupil, and then views through this eye and the prism an object such as is represented in Fig. 44, he will see two

FIG. 44.

images of the object, and when he is at a certain distance from the object the two images will appear in contact, as illustrated in Fig. 45. In this condition the prismatic displacement is exactly equal to the length (*A B*) of the object; hence, if the strength of the prism

FIG. 45.

and the distance at which the contact image is formed are known, the length *A B* can readily be determined. For instance, if the prism has a deflecting power of 1 prism-dioptre (each of the two component prisms having

one-half of this strength), and the contact position occurs at a distance of 1 metre, the length $A\,B$ must be 1 cm., and if the contact position occurs at a distance of 2 metres the length $A\,B$ must be 2 cm., and so on.

The curvature of the anterior surface of the cornea is estimated by measuring the diameter of the virtual image which is formed by reflection at this surface. The formulæ which determine the relative position and size of object and image in refraction are equally applicable for images formed by reflection. In reflection the medium traversed is unchanged—that is, $n = 1$, and, since the direction of motion is reversed, the angle of reflection is negative; in other words, any formula for refraction becomes adapted for reflection by making $n = -1$. Hence, formula (c), p. 56, may be used for determining the size of the image reflected from the cornea. Making the requisite change in (c), we derive $\frac{o}{i} = \frac{2\,l}{r}$ . . . (c_1) in which r is the radius of curvature, and l is the distance of the object (o) from the principal focus, this focus lying $\frac{r}{2}$ mm. behind the cornea. The size of the object o is known, as is also the distance of this object from the cornea; the problem is to measure the diameter of the image i, thereby making it possible to determine the radius r from the foregoing equation.[1]

In order to apply these principles with accuracy it is necessary that the double image should be viewed through a magnifying apparatus, which must also be provided with a scale indicating the size of the image or the radius of curvature to which it corresponds.

[1] In this formula it is assumed that spherical aberration may be neglected; that is, the diameter of the reflecting object is supposed to be small in comparison with its distance from the cornea. As this is not strictly true, a slight error is incurred in keratometric records as furnished by this formula.

The essential parts of this apparatus are a compound (achromatic) objective, by means of which there is formed a real aërial image of the reflected image seen in the cornea, and an eye-piece or compound (achromatic) convex lens, by which the examiner observes the aërial image without accommodation and with magnification. The whole apparatus must be enclosed in a tube darkened on the inside so as to exclude all extraneous light. The scale from which the readings are made varies in accordance with the method of obtaining the double image.

Helmholtz, in his ophthalmometer, produced the double images by means of two plates of glass inclined at an angle, which could be varied as required to effect the contact position of the images. The radius of curvature was calculated from the known relation between this and the angle of inclination of the plates. While this instrument is accurate in its workings, the process of manipulation is too complicated to permit of its being used for other than laboratory investigations.

The first keratometer adapted for clinical use was invented by Javal and Schiötz in 1882 and was improved by them in 1889. In this instrument the doubling of the image is produced by a Wollaston prism, which affords better illumination and achromatism than the glass prism; but with the adoption of a form of mire (object) better adapted for accurate reading, especially when transilluminated, the prism of ordinary glass may be substituted for the Wollaston prism without detriment. The prism occupies a fixed position in the tube of the instrument, and the degree of separation of images which it effects is known. This, in the 1889 model, is 2.94 mm. when the instrument is in adjustment; hence, by varying the diameter of the object the double image may be brought into the contact position, which corresponds to a diameter of 2.94 mm. for the corneal image, and also for the

aërial image seen by the observer, for in this instrument the cornea under examination is so placed that the virtual corneal image and the aërial image in the tube of the instrument have the same size.

The radius of curvature may readily be deduced from equation (c_1), since the distance of the cornea from the object and i (2.94 mm.) are constants whose values are known, and (o) the diameter of the object is capable of measurement; but such measurements are unnecessary, as the calculations have been made and recorded upon the scale of the instrument, from which the radius may be directly obtained.

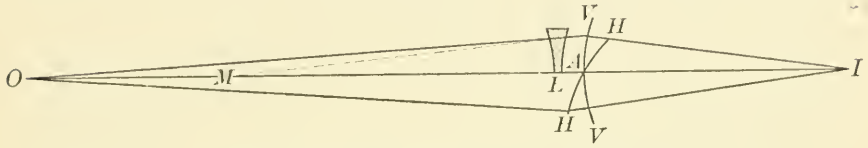
Other keratometers have in recent years been made which differ more or less from the Javal-Schiötz model. An extremely simple and efficient instrument is that known as the Chambers-Inskeep keratometer (Fig. 67). In this the separation is produced by a double prism, which is movable in the tube of the instrument, while the size of the reflecting object remains fixed. The separating power of the prism varies with its position, and on the scale attached to the sliding tube of the prism the radius of curvature corresponding to any position is indicated.[1]

Estimation of Corneal Astigmatism by Keratometry.—In Fig. 46, *H H* represents the horizontal and *V V* the vertical curvature of the cornea, the latter being the greater. In the horizontal refraction *I* is conjugate to *O*, and in the vertical refraction *I* is conjugate to *M*. In order that a pencil of light from *O* may be focused at a point (*I*) behind the cornea, a cylindrical lens must be placed before the eye such that in the vertical refraction the rays which proceed from *O* must

[1] In this instrument there is a theoretical objection to the dioptric scale, in that this is computed with too high a refractive index (1.35); but the *difference in readings* in the two principal meridians (which determines the astigmatism) is not appreciably greater than as recorded with the Javal-Schiötz instrument.

enter the eye as if proceeding from M. By means of this lens the astigmatism is corrected (all the rays are directed to a focus) and remains so, whatever spherical refraction the pencil may undergo *after* entering the cornea, as in passing through the crystalline lens.

FIG. 46.



Correction of astigmatism by a cylindrical lens.

The dioptric power of the lens which corrects the astigmatism is determined from the equation $\frac{1}{OL} - \frac{1}{ML} = \frac{1}{F'}$, or, if the distance between the eye and the lens is neglected, $\frac{1}{OA} - \frac{1}{MA} = \frac{1}{F}$ (7).

In the refraction by the cornea in the vertical meridian we have the equation $\frac{1}{MA} + \frac{n}{AI} = \frac{1}{F_1}$ (8), F_1 being the anterior focal length of the cornea in this meridian. In the horizontal meridian we have the equation $\frac{1}{OA} + \frac{n}{AI} = \frac{1}{F_2}$ (9), F_2 being the anterior focal length of the cornea in the horizontal meridian. Subtracting (9) from (8), we have $\frac{1}{MA} - \frac{1}{OA} = \frac{1}{F_1} - \frac{1}{F_2}$ (10), or from (7) $-\frac{1}{F} = \frac{1}{F_1} - \frac{1}{F_2}$. *That is, the dioptric power* ($\frac{1}{F}$) *of the correcting lens is equal to the difference between the reciprocals of the anterior focal lengths in the two principal meridians, provided we neglect the distance*

of the lens from the eye. In high astigmatism this neglect gives rise to an appreciable error.

The focal lengths are determined by the relation $F = \frac{r}{n-1}$; hence, having measured by keratometry the radius in the meridians of greatest and least curvature, we may readily ascertain the dioptric power of the lens which corrects the corneal astigmatism.

If it were desired to know the astigmatism in the anterior corneal refraction, we should assign the index of the cornea (1.377), but instead of this we assign the lower index of the aqueous humor (1.337). This gives a closer approximation to the total corneal astigmatism than if the index of the cornea were used, because the posterior corneal refraction is opposite to that which takes place at the anterior surface, and, assuming that the two surfaces are affected with the same kind of asymmetry, the astigmatism which occurs at this surface must in a measure neutralize that which occurs at the anterior surface; in other words, the total corneal astigmatism is less than the anterior corneal astigmatism.

Dioptric Graduation of Keratometers.—Since the strength of the correcting lens in dioptres is deduced from the expression $\frac{1}{F_1} - \frac{1}{F_2}$, it is customary to express in dioptres the reciprocal of the focal length as recorded on the keratometric scale; it is frequently stated, for instance, that the refraction of the cornea being 44 D. in one and 43 D. in the other principal meridian, the astigmatism is 1 D. Although this is convenient in keratometry, the fact must not be overlooked that the dioptre is the unit of lens-refraction, and that refraction in which the first and final media are not the same cannot be measured in terms of a lens-unit. In lens-refraction the two principal focal lengths are equal, while in refraction in which the first and final media

are different, $F' = n F$. Hence the refractive power of the cornea or of the eye cannot be expressed in dioptres, and serious errors are incurred by assuming that it can be so measured.[1]

[1] The Dioptric Power of the Cornea (author), in Ophthalmic Record, April, 1900, and April, 1901.

PART II.

THE NORMAL EYE.

CHAPTER IX.

REFRACTION OF THE NORMAL EYE.

The *refraction of the eye* is the expression used in ophthalmology to denote the relation between the position of the retina and of the posterior principal focus. The *static* refraction refers to this relation when the ciliary muscle is in complete relaxation; the *dynamic* refraction refers to the condition in which the ciliary muscle is contracted for the purpose of accommodation. Unless otherwise stated, the refraction of an eye indicates the static refraction.

Emmetropia.—When the principal focus lies at the intersection of the optic axis and retina, the ciliary muscle being relaxed, the eye is adapted to receive a clear image of a distant object. This is the ideal eye; it is regarded as the normal type of the human eye, and is called the emmetropic eye.[1]

Nature approximates but seldom attains emmetropia, and it is evident that the more the methods of measurement are refined the less frequent must be the occurrence of emmetropia. It is, therefore, necessary to assign a

[1] The word "emmetropia" was derived by Donders from the Greek ἔμμετρος (in due measure) and ὤψ (eye or vision).

limit within which the eye may be regarded as emmetropic. Practically this limit is marked by the weakest lens in the oculist's trial case; the eye is emmetropic when the weakest lens does not bring the retina and focus into greater proximity than they are without the lens.

Axial Length of the Normal Eye.—The normal eye, considering only its refractive properties, is an eye that deviates but slightly from emmetropia. It is without the range of probabilities that individual eyes should present uniformity either of curvature or of axial length; but, as the researches of Helmholtz and others show that the curvature varies only within comparatively small limits, so also anatomical examination of eyes which were known to be emmetropic, or nearly so, shows that their axial length varies to a correspondingly slight extent.

The distance from the anterior surface of the cornea to the retina, as determined for the schematic eye, is 23.23 mm. The thickness of the chorioid and sclera in the region of the macula is about 1 mm.; hence, theoretically, the antero-posterior diameter of the normal eye should be 24.23 mm. in length (Fig. 31). That it does not in fact deviate much from this average is attested by anatomists, who find the length of the normal eye to vary between 23 mm. and 25 mm. Merkel assigns 24.3 mm. as the average length; Sappey (average of 28 eyes of both sexes), 24.2 mm.; Macalester's *Anatomy* (1889), 24.27 mm.; Morris' *Anatomy* (1894), 24.5 mm., and Quain's *Anatomy* (1894), 24 mm.

The Surfaces and Media of the Eye.—It was shown by Helmholtz and others that the normal cornea very nearly resembles the small end of an ellipsoid of three unequal axes; that is, the curvature is greater near the centre than at the periphery, and greater in the vertical than in the horizontal meridian. Since the introduction of the Javal-Schiötz keratometer, measurements of

the anterior corneal curvature have been abundantly made. Among those who have made many observations at various distances from the corneal centre is Sulzer, and as the result of these investigations he draws the following conclusions as to the form of the cornea:[1]

"(*a*) The central region of the cornea differs but little from a segment of a sphere (leaving astigmatism out of account).

"(*b*) At a certain distance from the point of intersection of the visual line with the cornea—that is, as an average angular distance of 15° (which in the case of a cornea of mean curvature corresponds to a linear distance of 2 mm.)—the curvature begins abruptly to diminish. From this point to its periphery the corneal surface shows a progressively decreasing curvature assimilable to that which would be presented by a succession of ellipsoids of progressively increasing eccentricity.

"(*c*) Whether we assume the point of intersection of the visual line with the corneal surface, or the point of maximum curvature as representing the centre of the cornea, the corneal curvature does not diminish proportionally to the distance from this centre, and this whether the distance be measured on the two principal meridians or on the two halves of the same meridian; in other words, the cornea is not in any sense a surface of symmetrical curvature."

The normal cornea ordinarily presents its greatest curvature on the temporal side and the greatest flattening on the nasal side. The reason assigned for this is that the energetic action of the internal rectus in convergence diminishes the curvature of the medial portion of the cornea.

The average radius of curvature of the central portion of the cornea is, according to Helmholtz, 7.829 mm.

[1] As translated in Norris and Oliver's System of Diseases of the Eye, vol. ii. p. 134.

Other averages do not differ materially from this, and a radius of 7.8 mm. may be accepted as the standard for the normal eye. The limits within which the radius varies in emmetropia are comprised (as determined by Schiötz from a large number of examinations) between 7.2 mm. and 8.6 mm.

The curvature of the posterior surface of the cornea follows, in general, that of the anterior surface, but approximates somewhat more nearly the spherical form. The average radius of curvature, as ascertained by anatomists and by Tscherning with the aid of his ophthalmophakometer, is 6 mm.

The thickness of the central portion of the cornea is about 1 mm. (Tscherning and others).

The refractive index of the cornea, as determined by Aubert, is 1.377. Other estimates differ but slightly from this, as 1.3754 (Mathiessen) and 1.3825 (Macalester). Helmholtz, in his schematic eye, adopted 1.3365 as the common index of cornea, aqueous, and vitreous.[1]

The aqueous humor, being fluid, must be enclosed by a solid substance in order that its index may be determined. A small quantity of the aqueous may be placed at the apex of two inclined plates of glass; or it may be enclosed in a hollow lens (Helmholtz). The refractive effect of the glass being known, the remaining refraction which occurs in the passage of light through the combination represents the effect of the aqueous humor, from which the index can be derived by calculation. The index, as determined by Helmholtz, is 1.3365; according to Fleischer, it is 1.3373; accord-

[1] By thus assigning to the cornea the lower index of the aqueous and neglecting the posterior corneal refraction, the divergent effect of this refraction is almost but not entirely counterbalanced. The distance of the retina from the corneal summit in Helmholtz's schematic eye is 22.8 mm.; whereas, in our schematic eye, in which the other measurements do not materially differ from those of Helmholtz, this distance is 23.2 mm.

ing to Hirschberg, it is 1.3375. An index of 1.337 may be accepted as the standard for the normal eye.

The transparency of the cornea and aqueous humor, as direct inspection shows, is almost perfect. This transparency is attained in the cornea by the great regularity and close union of the individual lamellæ, and by the interposition of a cement substance of the same index as that of the lamellæ; otherwise reflection from the various strata would interfere with the passage of light. In health it is only by the most careful examination that we are able to detect any such reflection; but when the physiological arrangement is disturbed by disease, the cornea loses its transparency.

The estimation of the form of the crystalline lens is much more difficult than is the case with the cornea; but numerous measurements made by Helmholtz, Donders, Knapp, Woinow, Mauthner, and others—and which have recently been substantiated by Tscherning—show that the ciliary muscle being relaxed, the central portion of the anterior surface does not materially differ from a segment of a sphere having a radius of 10 mm., and that the corresponding portion of the posterior surface equally resembles a segment of a sphere having a radius of 6 mm. Since only the central portions of these surfaces are concerned in normal vision, we may in our calculations assume that they are spherical.

From a number of post-mortem measurements, made prior to the era of ophthalmometry, Brücke concluded that the anterior surface of the lens corresponded approximately with the surface generated by the revolution of an ellipse about its minor axis, while the posterior surface approximated a paraboloid of revolution.[1] Although neither surface is a true geometrical curve, yet Brücke's conclusions have, in general, been justi-

[1] Anat. Beschreibung des menschlichen Augapfels, 1847.

fied by measurements made by Tscherning and others with the ophthalmophakometer, inasmuch as these measurements show that the anterior surface presents its least curvature near the axis (when the eye is in relaxation), and that the posterior surface has its *greatest* curvature near the axis with a slight diminution at the periphery.

The decreasing peripheral curvature of the cornea tends to diminish aberration, but the increasing peripheral curvature of the anterior lens-surface and the very slightly decreasing curvature of the posterior surface are unfavorable to such action. The peculiar constitution of the lens, however, tends to counterbalance the excess of peripheral curvature. The nucleus has greater curvature and greater index than the cortex; consequently, light which passes near the axis and which, consequently, encounters the nucleus is more highly refracted than that which passes peripherally, thus escaping the action of the nucleus.

The average axial distance of the anterior surface of the cornea from the anterior surface of the crystalline lens is 3.6 mm., as determined by Helmholtz. The thickness of the cornea being regarded as 1 mm., the *depth of the anterior chamber* is 2.6 mm.

The average thickness of the lens, according to Helmholtz, is 3.6 mm.; according to Merkel, it is 3.7 mm., while Tscherning gives 4.1 mm. The lack of agreement between these figures is doubtless due in part to the fact that, on account of the difficulty of observation, the number of individuals examined by each investigator was not large enough to establish a correct average; but it seems certain that Helmholtz's estimate is too low. A thickness of 4 mm. (Listing) may be accepted as the standard for the normal eye.

The total or equivalent index of the lens may be derived with approximate accuracy by determining the indices of the outer, intermediate, and nuclear layers,

calculating therefrom the refractive power of a lens composed of these layers.[1] These determinations have been made by a number of investigators with fairly close approximation to uniformity. Woinow assigns as the indices of the outer, middle, and nuclear layers, respectively, 1.3968, 1.4216, and 1.4351, with 1.4387 as the equivalent index for the whole lens. Fleischer assigns 1.4371 as the equivalent index, which was adopted by Helmholtz in his later schematic eye. A more recent estimation by Stadtfelt assigns 1.435 as the equivalent index.

Listing (and Helmholtz in his first schematic eye) adopted the fraction $\frac{16}{11}$ (1.4545) as the index of the lens. That this is too high is evidenced by the insufficient length (22.2 mm.) of Listing's schematic eye.

Tscherning adopts 1.42, which, on the other hand, seems to be too low, since the length (24.75 mm.) of his schematic eye (representing an eyeball 25.75 mm. in length) exceeds the length of the emmetropic eye, as determined by anatomical examination.

For the purpose of calculation an index of 1.438 may be accepted as the average for the normal eye. Assigning this index to the lens, and 1.337 as the index of the aqueous and vitreous, we may readily determine from calculation that the crystalline lens (*in situ*) has a focal length of about 50 mm., corresponding to a dioptric power of 20 D.[2]

The crystalline lens, composed of numberless fibres, is divisible into three principal segments, and it not infrequently happens in a healthy eye that the indices of these separate segments are not quite uniform, thus

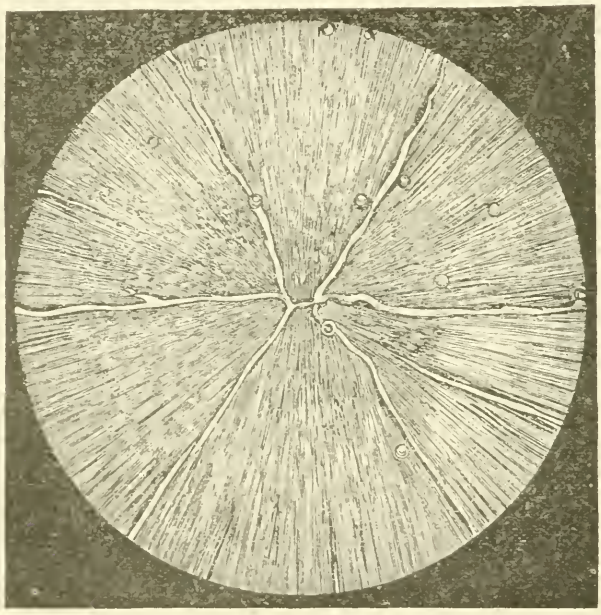
[1] Helmholtz also estimated the index of the lens by direct measurement of its focal length in air; and more recently Berlin (Arch. für Ophth., xliii., i.) has estimated the thickness and index from the ophthalmometric measurements as made in the living eye.

[2] Compare this with the power of the lens which must be placed in front of the eye as a substitute for the crystalline lens when this has been removed from the eye (p. 91).

giving rise to *irregular astigmatism*—a defect which, in fact, exists to some extent in all eyes.

The transparency of the lens is rendered imperfect by its heterogeneity of structure. Reflection from the interfibrillar substance and from the lines of union of the segments of the lens can, under favorable circumstances, be observed in the examination of an eye. We may

FIG. 47.



Lens spectrum. (Donders.)

observe the shadows (*lens-spectrum*) which defects of transparency cause to fall upon our retinas. This is most readily done by admitting to the eye, in a dark room, a beam of light which is diffused upon the retina by a strong convex or concave lens (15 D.) placed as near as possible to the eye (as in a trial frame). The light from a lamp may be reflected into the eye by the surface of another strong lens obliquely inclined (Nor-

ris), or by the ordinary concave forehead mirror. The examination of the lens-spectrum shows numerous opacities which would not otherwise be suspected (Fig. 47).

The lens becomes less transparent in old age, and sometimes assumes a yellowish hue. This physiological loss of transparency does not materially interfere with vision, but in a certain proportion of cases a still further change occurs—an infiltration between the fibres—whereby the lens loses its transparency, thus giving rise to the condition known as cataract.

In old age there is usually an increasing density of the cortex, which makes the whole lens approach homogeneity, the effect being a diminution of the refracting power of the lens; on the other hand, a pathological increase of density of the nucleus (frequently the precursor of cataract) increases the refractive power, thus giving rise to myopia.

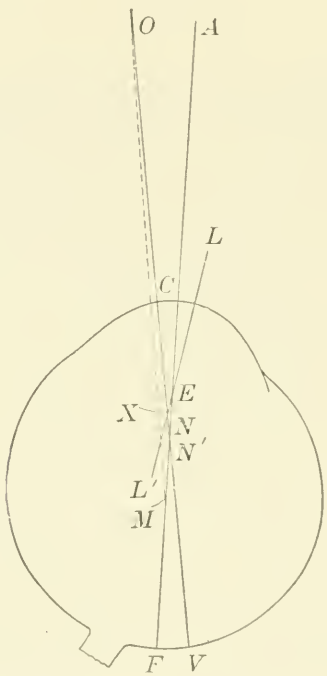
The refractive index of the vitreous is determined in the same way as is that of the aqueous. All estimates agree in assigning indices so nearly identical for these two media that they may be regarded as identical for the purpose of calculation.

The transparency of the vitreous body seems perfect when examined in the normal eye with the ophthalmoscope, but by looking at a uniformly bright light (as the sky) it is possible to see shadows which opacities in this substance cast upon our own retinas. These opacities are due to connective tissue cells and leucocytes which float about in the vitreous; the shadows to which they give rise are called *muscæ volitantes*. They do not interfere with vision except when in disease a pathological multiplication of these cells takes place.

Imperfect Centring of the Surfaces.—It has thus far been assumed that the refracting surfaces of the eye are all centred on a common axis, for otherwise they do not form a regular optical system capable of producing a well-defined image. It is found by numerous meas-

urements that these surfaces do not in this respect form a perfect optical system. This is illustrated in Fig. 48, in which $L\ L'$ represents the major axis of the ellipse of which the cornea is a segment. The curvature of the cornea for a short distance on each side of L may be considered symmetrical, and $L\ L'$ would be the

FIG. 48.



The angles alpha and gamma. $L\ L'$ is the major axis of the ellipse of which the cornea forms a part. The angle $L\ X\ O$, which the axis of the ellipse makes with the visual line $O\ N$, is called *alpha*. The angle $O\ M\ A$, which the line of fixation makes with the optic axis, is called *gamma*. $O\ M\ A$ is practically equal to $O\ N\ A$, and $O\ N\ A$ is equal to $F\ N'\ V$. Hence, practically gamma measures the angular distance of the fovea from the posterior focus.

proper axis of the cornea, but this line is appreciably removed from the axis of the crystalline lens. The line which most nearly forms a common axis for cornea and lens is $A\ F$, which passes through the centre of the corneal surface and the centre of rotation of the eyeball.

The axis of the crystalline lens approximately coincides with this line. Helmholtz and Knapp found the summit of the anterior surface of the lens to be sometimes situated as much as two degrees to the temporal side of the optic axis. More recent measurements by Tscherning indicate that, *as a rule*, the antero-posterior axis of the lens is in such position as if the lens were rotated outward (from a proper centring) around a vertical axis from three to seven degrees, and in some cases around a transverse axis as much as three degrees.

It is, therefore, apparent that the eye is not a perfect optical apparatus—the curved surfaces are not perfectly regular, the media are not perfectly transparent, and, in the strictest sense, there is no common optic axis.

The Iris.—In compensation for this irregularity there is in the eye an adjustable diaphragm—the *iris*—perforated at its centre by a circular aperture—the pupil—through which light passes into the eye. All but the most central rays, which are least affected by the optical imperfections of the eye, are thus prevented by the iris from entering the eye.

The size of the pupil is regulated by the sphincter and dilator muscles of the iris. Stimulation of the retina by a bright light produces by reflex action a contraction of the pupil; when this stimulus is removed by feeble illumination the pupil dilates so as to permit more light to enter the eye. The pupil also contracts consensually with accommodation.

Insensitiveness of the Periphery of the Retina.—Another provision of nature to prevent confusion from ill-defined images is the comparative insensitiveness of the peripheral portions of the retina. Although the field of vision in a healthy eye embraces a large area, yet within a very small part of this area is a clear mental impression of an external object received. Thus the fact that the image itself is poorly defined on the retina is not noticed. If, however, an object worthy of atten-

tion comes within this field of indistinct vision, the eye is turned by its muscular apparatus into proper position to receive a clear image. Since a clear image is possible only in the region near the optic axis, it follows that if the eye is a well-constructed apparatus the most sensitive portion of the retina must correspond to that portion upon which the clearest image will be projected. The portion of retina adapted for distinct vision consists of an elliptical area, the length of whose greatest or horizontal diameter is about 2 mm., and that of the least or vertical diameter is about 1 mm. This area is called, from its post-mortem appearance, the *macula lutea* or *yellow spot*. But the region of most acute vision does not occupy all or even the greater part of this area. The *fovea centralis*, upon which falls the image of every object attracting mental attention, does not exceed 0.4 mm. in diameter. It thus appears that that part of the retinal image which is perceived as distinct vision is extremely small. The portion of retina which it covers may be regarded as a plane surface, and if it intersects the optic axis at its posterior focus, this part of the retina may be regarded as coinciding in position with the posterior focal plane of the optical system of the eye.

Eccentric Position of the Macula. — We have learned that if the eye is well adapted to its needs, the fovea must lie at or near the intersection of the retina and optic axis. As we have found that nature has not made the optical apparatus of the eye with mathematical exactness, so we must not expect to find the fovea placed with uniformity upon the optic axis. In fact, anatomical examination shows that it is seldom so placed. It may lie to the outer or inner side of the axis, or above or below it.

As a result of this faulty position of the fovea the image of greatest sharpness, that which has its central point on the optic axis, does not fall upon the fovea.

This is illustrated in Fig. 48. The optic axis is represented by *A F;* the posterior focus by *F;* the fovea centralis by *V;* and the nodal points by *N* and *N'*. If one desires to look at the point *O*, the position of the eye will not be such that the axis *A F* is directed to *O*, for if it were the image would fall at *F*, on the axis, and not at the fovea, as is necessary for distinct vision; the eye must be so directed as to cause the line *O N N' V* to pass through the fovea. Since this line passes through the nodal points, there is no angular displacement, and only the slight lateral displacement due to the very short distance between these points. This line forms the axis of an oblique pencil, and a small oblique pencil from *O* will be focused at the fovea *V*. Since the line *O N N' V* (which may be regarded as a straight line, for the lateral displacement is inappreciable) indicates the direction in which the point *O* lies, it is called the *line of vision*. The point *O*, to which attention is directed, is called the *point of fixation*. The line *O M*, which connects the point of fixation and the centre of rotation of the eyeball, is called the *line of fixation*. The centre of rotation lies about 14 mm. behind the anterior surface of the cornea, or about 7 mm. behind the merged nodal points and 10 mm. from the posterior surface of the sclera.

The Angles Alpha and Gamma.—There are included by these various lines the following angles, with which the ophthalmologist should be familiar: (1) The angle *L N O*, which the major axis of the corneal ellipse makes with the visual line; this is called the angle *alpha* (α). (2) The angle *O M A*, which the line of fixation makes with the optic axis; this is called *gamma* (γ). (3) The angle *O N A*, which the visual line makes with the optic axis; this angle is the same as *F N' V*, which measures the angular distance of the fovea from the posterior focus of the eye. When the point *O* is much removed from the eye in comparison

with the distance *N M*, the lines *O M* and *O N* are very nearly parallel, and the angle *O M A* may be regarded as equal to *O N A*, and for practical purposes the angle *gamma* may be said to be the *angle which the visual line makes with the optic axis*, or it is equal to the angular distance of the fovea from the optic axis.

The angle alpha is positive when the apex of the corneal ellipse lies to the temporal side of the visual line, as in the figure. This is the most frequent condition; but sometimes the corneal apex lies to the inner side of the visual line, and alpha is then *negative;* or the axis of the corneal ellipse and the visual line may coincide, thus making alpha equal to zero.

The angle *L E C*, which the major axis makes with the optic axis, is small, not usually exceeding one or two degrees; hence, regarding *O N A* as the equivalent of gamma, we see that alpha is slightly greater or less than gamma, according as these have the same or opposite sign.

These angles have an important bearing upon the apparent position of the eye. We judge of the direction in which an eye is looking by the position of the corneal apex and of the pupil, not by the visual line, which we cannot see. Consequently, a pair of eyes looking at a distant object and having the visual lines parallel appear to diverge if there is a large positive gamma angle, and to converge if this angle is negative.

Donders found gamma as great as ten degrees in some eyes in the horizontal meridian. The angular distance between the fovea and the focus is not so great in other meridians.

Donders also found that gamma is ordinarily positive and greatest in hyperopes, and least or even negative in myopes.[1] In this way is explained the *apparent*

[1] This is in part, at least, because the optic axis lies nearer the optic disk in hyperopia than in myopia. (Compare Figs. 32 and 33.)

divergent strabismus that sometimes exists in hyperopes and the *apparent convergent strabismus* of myopes.

Function of the Chorioidal and Retinal Pigment.—The inner surface of a photographic camera is coated black for the purpose of absorbing all extraneous light. In the eye the pigment of the chorioid and retina performs this function, thus preventing internal reflections, with consequent marring of images.

DYNAMIC REFRACTION.

In emmetropia the macula lutea coincides with the posterior principal focal plane of the eye, and if otherwise normal, the eye fulfills the conditions necessary to receive a clear image of a distant object; but the image of a near object would be formed at its conjugate focal plane, behind the posterior principal focal plane, and since light would be intercepted by the retina before reaching this conjugate focal plane, the rays from any point of the object, not having reached their intersecting point, would form upon the retina a diffusion-circle. The image of the object, being an aggregation of such diffusion-circles, would be blurred.

When it is desired to bring (in an optical apparatus) the screen on which the image is projected and the conjugate focus into apposition, three devices are available: (1) The position of the screen may be altered; (2) the distances between the refracting surfaces may be varied; (3) an additional lens may be placed before the optical system. The eye possesses no means by which it can vary the position of the intercepting screen or retina; but it can avail itself of the last two devices, for by a most admirable mechanism it is enabled to vary the distance between the cornea and anterior surface of the lens, and at the same time to increase the curvature of this lens, which in effect is equivalent to

the addition of a lens. This adaptation of the eye for varying distances has already been defined as *accommodation.*

The first definite proofs as to the manner in which accommodation is performed were made by Thomas Young. By means of measurements on his own eyes, he showed that there was no change in curvature of the cornea, nor in length of the eye during accommodation. The results of this investigation were published in a memoir, which has recently been republished by Tscherning.

The reflected images which are formed at the surfaces of the cornea and lens were first noticed by Purkinje (about 1823), whose name they bear; but it was Langenbeck who, in 1849, first made use of these images for ascertaining the curvature of the lens during accommodation. He observed that the image as reflected from the anterior surface of the lens became smaller and approached that reflected from the anterior surface of the cornea during accommodation; from this he inferred that the anterior surface of the lens approached the cornea and that its curvature was increased. Cramer improved the experiments of Langenbeck and invented an instrument for magnifying the reflected images, by means of which they could be more accurately studied. Finally, Helmholtz noticed that the curvature of the posterior surface of the lens was also slightly increased. The change in size of the image as reflected from this surface, being so slight, had escaped the notice of the other observers. With the aid of the ophthalmometer invented by him, Helmholtz was enabled to measure precisely the curvature and position of the various surfaces during the exercise of accommodation. It was thus firmly established that the cornea undergoes no change whatever in accommodation, that the anterior surface of the lens approaches the cornea and assumes greater convexity, and that the posterior surface is not

appreciably changed in position, though its curvature is slightly increased.

From these investigations Helmholtz concluded that, 10 mm. being the average radius of the anterior surface of the lens during relaxation, 6 mm. is the average radius of this surface during maximum accommodation in young adults, and that under the same condition the radius of the posterior surface of the lens decreases from 6 mm. to 5.5 mm., and the thickness of the lens increases from 3.6 mm. to 4 mm. Since the position of the posterior surface remains unchanged, the anterior surface of the lens becomes 0.4 mm. nearer the cornea.

Anatomy of the Ciliary Region.—In order that we may understand how these changes in the crystalline lens are accomplished we must first call to mind the essentials of the anatomy of this lens and of the ciliary region of the eye. The lens, whose general form and size have already been described, is fibrillar in structure and varies in consistency according to the age of the individual. In infancy the entire lens-substance is of a soft semifluid or gelatinous nature; but with increasing age the central or nuclear portion gradually loses water and becomes firmer in consistency. By the time adult life is reached the most central part has become weakly solidified, thus forming a nucleus. This process continues so that the nucleus increases in size and hardness as the maturity of the individual advances. The outer or cortical portion also increases in firmness, and in old age the entire lens is transformed into a solid mass, with a nucleus of still greater hardness.

The lens-substance is enclosed in a delicate, transparent capsule—a contractile membrane resembling sarcolemma in structure.

The lens, enclosed in its capsule, is supported in its position between the iris and aqueous humor on one

side and the vitreous body on the other by a delicate ligament—the zonule of Zinn, or suspensory ligament of the lens. This ligament is attached to the anterior and posterior surfaces of the capsule near the equator or peripheral border of the lens.

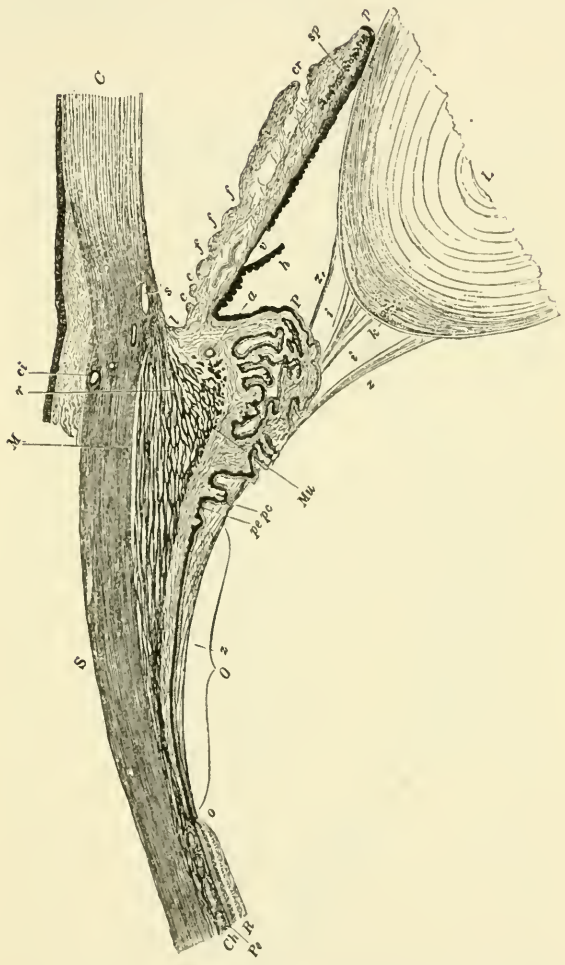
The ligament, thus attached to the lens, has its outer border attached to the ciliary processes and to the depressions between these processes. Opposite to the equator of the lens, about 0.5 mm. distant and projecting anteriorly, lie the ciliary processes, which consist of a network of bloodvessels and chorioidal pigment lining the inner circumference of the sclerocorneal ring, and extending backward to be gradually merged with the chorioid.

The ciliary muscle lies beneath these processes. This muscle is composed of non-striated fibres and consists of two parts. The larger portion is formed of meridional fibres (Brücke's muscle), which are attached anteriorly with firm union to the sclerocorneal junction and neighboring sclera. The fibres of this part, passing backward, are inserted into the anterior portion of the chorioid. This is the most external part of the muscle, its outer surface being in contact with the sclera. To the inner side of this and adjoining the ciliary processes is the second or transverse part of the muscle, called the *annular muscle of Müller*. This consists of a circular band of fibres surrounding the margin of the iris. Some of the fibres, after proceeding for a certain distance transversely, penetrate this part of the muscle obliquely and join the first or meridional portion (Fig. 49).

The relative proportion in size of the two divisions of the muscle is said to be about 10 of the first to 1 of the second in emmetropia.[1] The sphincter of the iris and the ciliary muscle are innervated by the third nerve,

[1] This proportion differs in different states of refraction, the circular portion being most abundant in hyperopia and least so, or even absent, in high myopia. (Iwanoff.)

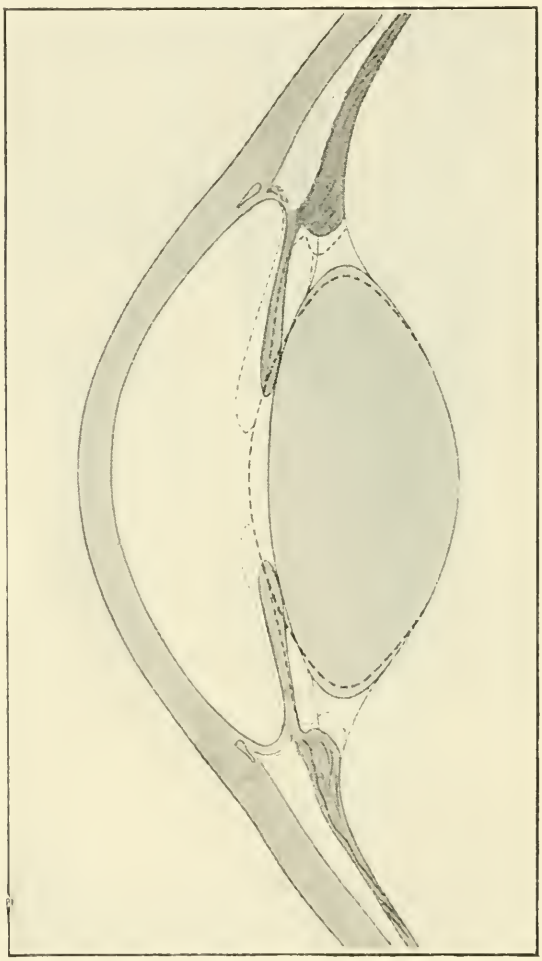
FIG. 49.



Meridional section through anterior part of the eye, showing the ciliary body and iris, with neighboring structures. *C.* Cornea. *S.* Sclera. *s.* Schlemm's canal. *ci.* Anterior ciliary vein. *l.* Ligamentum pectinatum. *cr.* Crypts in circulus minor iridis. *c.* Periphery of iris. *f.* Contraction furrow. *hvp.* Retinal pigment of iris. *v.* Anterior layer of retinal pigment. *p.* Pupillary margin. *sp.* Cross-section of sphincter pupillæ. *M.* Longitudinal fibres of ciliary muscle, Brücke's portion. *Mu.* Circular fibres or Müller's portion. *r.* Transition or radial fibres. *a.* Circulus arteriosis iridis major. *P.* Ciliary processes. *pe.* Pigment cellular layer. *Pe.* Pigment epithelium. *pc.* Non-pigmented layer. *R.* Retina. *O.* Orbiculus ciliaris. *o.* Ora serrata. *Ch.* Chorioid. *z.* Fibres of zonule of Zinn. z_1. Free portion of zonula. *i.* Canal of Petit. *L.* Lens. Magnified 14 times. (After Fuchs.)

acting through the ciliary ganglion. These muscles are, therefore, involuntary in their action; contraction occurs

FIG. 50.



The crystalline lens and ciliary region. The dotted outline represents the changes which occur in accommodation.

as the result of reflex stimulation. We have no control whatever over the pupillary movements, but to a certain extent (largely through the association of convergence)

we may cultivate the power of voluntarily relaxing or contracting the ciliary muscle.

Helmholtz's Theory.—It was Helmholtz also who, after demonstrating the changes which occur in the lens during accommodation, first presented an explanation of the way in which these changes are accomplished. He assumed that, the anterior extremity of the ciliary muscle being attached to the firm sclerocorneal junction, contraction of this muscle would draw forward the anterior portion of the chorioid, to which the posterior extremity is attached. In consequence of this forward motion the ciliary processes and the suspensory ligament of the lens would also be drawn forward, and relaxation of this ligament would occur.

Assuming, with Helmholtz, that this relaxation and forward movement actually occur, one needs only to glance at Fig. 50, and to bear in mind the constitution of the lens in order to understand what will, in a general way, be the effect of this relaxation upon the shape and position of the lens.[1] In childhood, at which period accommodation is most active, the lens consists of a semifluid or gelatinous mass enclosed in a contractile capsule. The tendency of such a mass is always to *approximate* the spherical form. This is because a fixed volume of matter presents its smallest area of external surface when in this form, and what is known in physics as the *surface-tension* of the mass (together with the contractility of the capsule) is ever acting to reduce this surface-area. A simple illustration of this is afforded by a thin India-rubber bag distended with water or other fluid substance. If by pressure or traction on the bag the shape is altered, its original form will at once be resumed on release from pressure.

[1] Helmholtz believed the meridional fibres to be the chief factor in accomplishing this relaxation, but it is now recognized that the annular muscle of Müller plays an important part by diminishing the circumference of the zone of attachment of the suspensory ligament.

Although the tendency of such a body is to assume the spherical form, there may be a number of counterbalancing forces which prevent this form from being attained. In the case of the India-rubber bag, for instance, the structure of the latter may be such as to give an oval form to the body. Similarly, in the lens the form is modified by the capsule, and even if the lens-substance were perfectly fluid and if no external traction were exercised, a perfectly spherical form would not be assumed; but, in a general way, this form would be approximated.

In its normal position in the eye the pressure or traction by the suspensory ligament causes the lens to assume an ovoidal form. We observe (Fig. 50) that the anterior part of this ligament is shorter than that which is attached to the posterior surface of the lens, and that, as a result of this, the tension is greater upon the anterior than upon the posterior surface. As the tension is greater upon the anterior surface, so the effect of relaxation must be greater upon this than upon the posterior surface. Hence, if the lens has not become solidified in its flattened form, relaxation of the ligament allows the anterior surface to advance with a decided increase of curvature; while, the effect of relaxation of the posterior portion of the ligament being less marked, the posterior surface undergoes only slight increase of curvature with no measurable change of position.

Experimental Observations. — The first experimental observations made for the purpose of ascertaining whether the changes which take place in accommodation agree with the assumption of Helmholtz were undertaken by Hensen and Voelckers.[1] Their experiments, which were made chiefly upon the lower animals,

[1] Experimentaluntersuchung über den Mechanismus der Accommodation, Kiel, 1868, and Arch. f. Ophth., 1873, xix., 1.

consisted in exposing the ciliary ganglion and ciliary region, and observing the changes caused by irritation of the ciliary nerves. By this means they were able to demonstrate: (1) A contraction of the pupil with a forward motion of the pupillary border of the iris, and of the anterior surface of the lens, with an increase of curvature of this surface; (2) contraction of the ciliary muscle with advancement of the ciliary processes and anterior portion of the chorioid.

The changes which occur in the living human eye in accommodation were first made a subject of study by Coccius and Hjort. Coccius[1] observed eyes upon which peripheral iridectomies had been performed, and Hjort[2] made use of a person in whom there existed total aniridia, the result of accident. The changes which these investigators were able to detect resembled those which had been described by Hensen and Voelckers as occurring in lower animals. Coccius and Hjort were further enabled to view the ciliary region directly and to demonstrate that the ciliary processes advance during accommodation. Since, as these processes advance, they also become more prominent, the experimenters were led to believe that the efferent veins from this region were compressed, and that, in consequence, there was an increase of intra-ocular pressure. Subsequent investigations, however, have shown that there is no such increase of pressure during accommodation.

Resting upon these demonstrations, Helmholtz's theory of accommodation has received almost universal acceptance, but its correctness has been denied by Tscherning,[3] Schoen,[4] and others.

Tscherning's Theory.—Tscherning, who is the chief advocate of the counter-theory that accommodation is

[1] Coccius, Der Mechanismus der Accommodation, Leipzig, 1868.
[2] Hjort, Klin. Monatsbl. für Augenheilkunde, xiv., p. 205.
[3] Tscherning, Physiologic Optics (American edition), p. 171.
[4] Schoen, Arch. f. die ges. Phys., lix., p. 427.

produced, not by relaxation but by increased tension of the suspensory ligament, gives the following reasons for rejecting Helmholtz's theory:

"1. The increase of refraction of the lens in accommodation takes place only near the apex of the lens. This is established by study of the spherical aberration of the eye; aberration, which is positive when the eye is at rest, diminishes or even becomes negative in maximum accommodation.

"2. Measurements with the ophthalmophakometer show that the increase of curvature of the anterior surface of the lens is confined to the portion near the summit of the lens, and that the *anterior surface does not move forward*, but remains stationary or moves slightly backward, while the posterior surface moves appreciably backward.[1]

"3. Experiments made upon the eyes of animals show that traction upon the ligament of the lens produces an increase of curvature near the summits of the surfaces, and relaxation produces diminution of curvature."

Helmholtz confined his measurements to the portion of the surfaces near the optic axis, but Tscherning has, with the aid of his ophthalmophakometer, been enabled to measure the curvature of more peripheral parts of the lens-surfaces. Confining these measurements chiefly to the anterior surface (which plays the more important part in accommodation), he finds that the curvature diminishes very rapidly as the distance from the axis increases. From a number of such measurements he

[1] In his latest work (Physiologic Optics) Tscherning expresses doubts as to the occurrence of increased thickness of the lens in accommodation, believing that the accuracy of ophthalmometry is insufficient to exclude an error as great as the supposed increase of thickness. His judgment is not, however, unbiased, since an increase in thickness is inexplicable by his theory; and we must regard the fact that (with all other observers) the possible error is almost uniformly in favor of increased thickness as strongly corroborative of its occurrence.

concludes that the anterior surface of the lens assumes in accommodation a form closely approximating a hyperboloid—a form which he believes inconsistent with Helmholtz's theory.

All that is required by Helmholtz's theory is that in relaxation of the suspensory ligament the lens tends to assume a more spheroidal form. This tendency is manifested by an increase of thickness in the least diameter and by an increase of curvature in the region of least resistance. The form of curvature is, doubtless, influenced by the structure of the capsule and, possibly, by other factors which, from their nature, are undemonstrable. While, therefore, there is no inconsistency between Helmholtz's theory and Tscherning's measurements, it is yet not improbable that the peripheral diminution of curvature has been overestimated by Tscherning. Owing to the difficulty of observation and to the fact that allowance must be made for the refractive effect of the cornea and aqueous, a slight amount of error cannot be excluded from the results obtained. Instead of the hyperboloidal curvature described by Tscherning, it seems more probable that when the pressure is removed from the anterior surface in accommodation, this surface assumes a form approximating that maintained in a state of rest by the posterior surface, which is but slightly affected by traction of the ligament. This surface presents its greatest curvature at the centre (axial portion), with a diminishing curvature toward the periphery, resembling in a general way a paraboloid.

The diminution of spherical aberration which occurs in accommodation, as shown by Tscherning, is a direct sequence of the peripherally diminishing curvature, and consequently it is not inconsistent with Helmholtz's theory.

As regards Tscherning's experiments upon the eyes of animals, it should be noted that traction made upon

the suspensory ligament can cause increase of curvature at the summit only when the lens has a hard nucleus surrounded by soft cortical matter, as may be found in the lens of the adult ox—the animal upon which Tscherning's examinations were made. In the lens of the calf traction causes flattening at the summits of the surfaces.[1] It is evident, therefore, that Tscherning's experiments do not substantiate his theory, for the solid nucleus, which is necessary (as admitted by Tscherning) in order that traction may cause an increase of curvature, does not exist in childhood—the period of greatest accommodative activity.

The foremost antagonist of Tscherning's theory is Hess,[2] who has conducted experiments to prove that the suspensory ligament is in a relaxed condition during accommodation. The experiments of Hess consisted chiefly in demonstrating: (1) The correctness of the observations of Coccius and Hjort; (2) a sinking of the lens from gravity when the eye makes a maximum effort of accommodation; and (3) a change of position of the lens during accommodation with change of position of the head; that is, a forward motion with the head inclined forward (downward) and a backward motion with the head thrown back.

Equivalent Index of the Lens in Accommodation.—In the calculations by which the total index of the lens has been derived, the relative curvatures of cortex and nucleus, as they exist in a state of relaxation, have constituted the basis upon which the process rests. Since this relation is changed in accommodation, there is no assurance that the index of the equivalent homogeneous lens is the same in accommodation as in relaxation. If the increase of cortical curvature occurs without a like increase of nuclear curvature, the total index

[1] Theory of Accommodation (author), in Arch. of Ophth., July, 1900.
[2] Arch. für Ophth., xlii., 3, p. 288, and xliii., 3, p. 477.

must be diminished, while, on the other hand, if the nuclear curvature increases also, and to a greater extent than the cortical curvature, the total index is increased. The latter condition must be assumed to occur, because calculations show that a higher index is required for the lens in accommodation than in relaxation, in order that the near-point of the eye as determined by these calculations may agree with that as determined experimentally.[1]

The increase of nuclear curvature, which must be assumed, results from the fibrillar structure of the lens. When, from relaxation of the ligament, the cortical fibres advance in the region of the anterior summit, there must be at the same time a slight advance of the nuclear fibres, and a slight advance of these fibres will cause a greater increase of curvature than a greater advance of the cortical fibres.

Length of Time Required for Accommodation.—Experiments have been conducted for the purpose of ascertaining how long a period of time is required for the production and relaxation of accommodation.[2] It requires from one to two seconds to change the adaptation from infinity to the usual reading distance, and about one-half of this period to produce the inverse change. The length of time required for these acts varies in different persons and at different ages, a greater time being required as the crystalline lens becomes more solid in consistency.

Range of Accommodation.—Since the solidity of the lens undergoes a gradual increase from infancy to old age, it follows that the power of this lens to assume greater convexity under the relaxing influence of the ciliary muscle must suffer a gradual diminution with

[1] Equivalent Refractive Index of the Lens in Accommodation (author), in Arch. of Ophth., March, 1901.

[2] Vierordt and Aeby, quoted by Landolt, Refraction and Accommodation of the Eye, p. 165.

advancing years. At ten years of age, the youngest period of life at which accommodation can well be measured, the normal eye can accommodate for a point about 70 mm. from the eye; at twenty years of age the nearest point for which the eye can accommodate is 100 mm.; at forty-five years the nearest point is about $\frac{1}{4}$ metre; and at seventy years little or no accommodative power remains.

The nearest point for which an eye can accommodate is called the *near-point of accommodation*.

Since the increase of curvature of the lens during accommodation has the same effect as the addition of a convex spherical lens placed in contact with the cornea, we may measure the accommodative power by its equivalent lens. An emmetropic eye adapted for distant vision exercises no accommodation. The far-point of this eye is at infinity. The same eye when viewing an object distant $\frac{1}{2}$ metre would require a convex lens of 2 D. to produce distinct vision, if the lens were placed in front of the eye and as near as possible to it. If the lens is replaced by accommodation, 2 D. is the lens-equivalent, and this may be taken as the measure of the accommodation exercised. Similarly an eye viewing an object $\frac{1}{4}$ metre distant requires either a convex lens of 4 D. or 4 dioptres of accommodation.

The dioptric equivalent of the accommodative power of an eye is called the *amplitude* or *range of accommodation*.

The following table gives Donders' estimate of the range of accommodation of the eye at different ages:

Age	10	15	20	25	30	35	40	45	50	55	60	65	70	75
Dioptres[1]	14	12	10	8.5	7	5.5	4.5	3.5	2.5	1.75	1	0.75	0.25	0

While the range of accommodation is the same in ametropia (except in high degrees) as in emmetropia, the position of the near-point varies with the state of

[1] Adapted from the inch system by Landolt.

refraction. Thus, in the emmetropic eye with the far-point at infinity and the near-point at $\frac{1}{4}$ metre, the region of accommodation embraces the whole distance from infinity to within $\frac{1}{4}$ metre from the eye. In the case of a hyperopic eye a certain amount of accommodation must be exercised to procure distinct distant vision, leaving only what remains for near vision. If in an eye having 4 D. of accommodation there is hyperopia of 2 D., only 2 D. will remain for adapting the eye to near vision and nothing nearer than $\frac{1}{2}$ metre can be seen distinctly.

The far-point of the hyperopic eye is negative—that is, only convergent pencils can be focused by it without accommodation; but as no convergent pencils enter the eye (except through artificial systems), the negative part of the range of vision is of no use in ordinary vision, and practically the far-point of the hyperopic eye lies at infinity. Hence, in the aforementioned case the range of vision is from infinity to a point distant $\frac{1}{2}$ metre from the eye.

If, on the other hand, there is myopia of 2 D., the far-point lies $\frac{1}{2}$ metre in front of the eye. Beyond this point distinct vision is not possible; but for near vision, if this eye can command 4 D. of accommodation in addition to the 2 D. of myopia, its lens-equivalent is equal in all to 6 D. The near-point of distinct vision is, therefore, $\frac{1}{6}$ metre from the eye, and the range of vision embraces only the interval lying between the far-point, $\frac{1}{2}$ metre, and the near-point, $\frac{1}{6}$ metre, respectively, from the eye.

The emmetropic eye requires 4 D. of accommodation to see distinctly at $\frac{1}{4}$ metre; the eye having 2 D. of hyperopia requires 6 D.; and the eye having 2 D. of myopia requires 2 D. of accommodation for vision at this distance.

It will be noticed that while 1 D. of accommodation will change the adaptation of the eye from infinity to a

point situated 1 metre from the eye, an additional dioptre will effect a change from 1 metre to $\frac{1}{2}$ metre only, and another addition of 1 D. will effect a change from $\frac{1}{2}$ to $\frac{1}{3}$ metre. Thus as an object approaches the eye, the amount of accommodation necessary to give distinct vision increases at a rapidly increasing rate.

In considering near vision we should also bear in mind that the addition of each dioptre of accommodation requires a greater effort than that of the preceding dioptre.

Reserve Accommodation.—Furthermore, it is not possible to exercise all the accommodative power for any length of time. Investigations by Landolt have shown that about one-third of this power must be held in reserve, if continuous work is to be done. A person having just 3 D. of accommodative power could not read continuously at $\frac{1}{3}$ metre; in order to do this he must have at least 4.5 D. at his disposal, for he must keep in reserve 1.5 D. ($\frac{1}{3}$ of 4.5 D.), leaving 3 D. for actual use.

CHAPTER X.

MOTILITY OF THE NORMAL EYE.

THERE are attached to each eyeball for the purpose of controlling its movements six muscles: four recti (internal, external, superior, and inferior) and two oblique (superior and inferior). These six muscles are called *extrinsic* or extra-ocular in contradistinction to the ciliary and iritic muscles, which are the intrinsic muscles of the eye.

The four recti muscles arise from the margin of the optic foramen, and in their passage forward bound a funnel-shaped space, in the hollow of the basal portion of which the eyeball is inserted (Fig. 51). The *internal rectus* is attached anteriorly to the sclera on the nasal side of the eye, about 5 mm. behind the margin of the cornea; the *inferior rectus* is similarly attached at the lower side, at a distance of 6 mm. behind the cornea; the *external rectus* is attached at the temporal side, about 7 mm. behind the cornea; the *superior rectus* is attached above, about 8 mm. behind the cornea.[1] It thus appears that the internal rectus is most favorably attached for rotating the eye, while the inferior muscle holds the second place; this is in accordance with physiological requirements, since the greatest tax falls upon these two muscles.

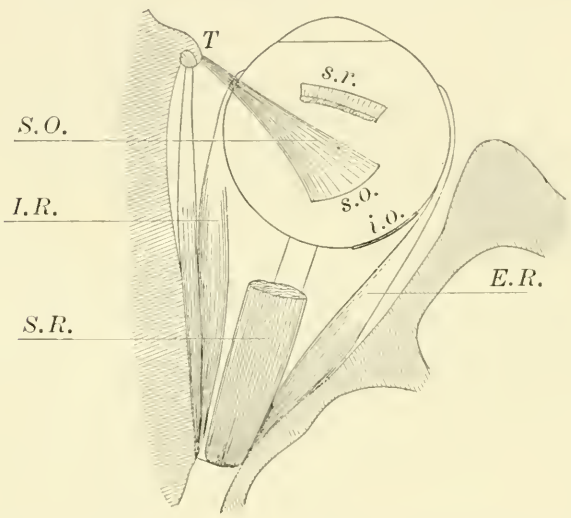
The breadth of the tendons at their lines of insertion varies from 10 mm. to 11 mm., except for the inferior

[1] These are average measurements as determined by Motais. They may be easily remembered, since they correspond to the consecutive numbers, 5, 6, 7, and 8. In the case of the superior and inferior recti, whose lines of insertion are obliquely inclined to the corneal margin, the measurements refer to the central points of the attachments.

rectus, the breadth of which is somewhat less—from 9 mm. to 10 mm.

The *superior oblique* arises from the border of the optic foramen, but, unlike the recti, it is not directly attached to the eyeball; it extends forward to the upper and inner angle of the orbit, where it passes through

FIG. 51.

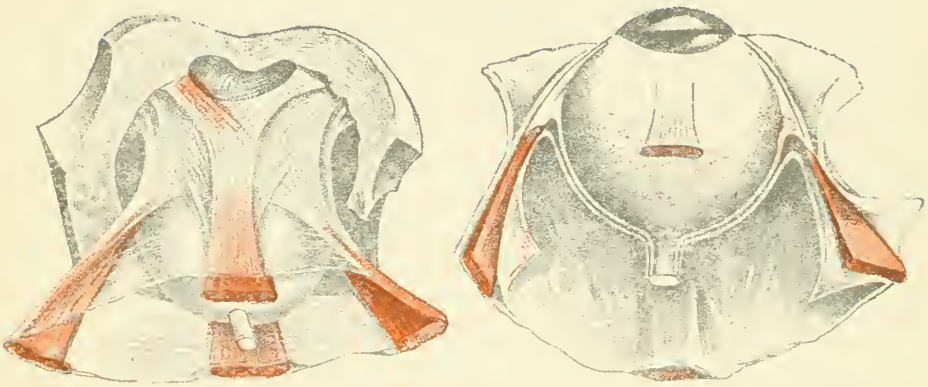


Showing the origin and attachment of the extra-ocular muscles and the position of the eyeball in the orbit. The letter *T* represents the trochlea, which is at the inner and upper angle of the orbit; *E. R.* represents the external rectus, *I. R.* the internal, and *S. R.* the superior rectus; *S. O.* represents the superior oblique. The inferior rectus and the inferior oblique are not shown. The scleral attachment of the superior rectus is represented by *s. r.*, that of the superior oblique by *s. o.*, and that of the inferior oblique by *i. o.* (After Fuchs.)

a loop of fascia (the *trochlea*), then, continuing backward and outward and passing beneath the superior rectus, it is inserted into the upper part of the sclera, behind the equator.

The *inferior oblique* arises from the lower margin of the orbit near the inner angle, and, proceeding outward and backward below the inferior rectus, is inserted into the outer part of the sclera, behind the equator.

PLATE I.



Capsule of Tenon, Intermuscular Fascia, and Check Ligaments. (Motais.)

All these muscles are surrounded by fascia, which also (under the name of *Tenon's capsule*, Plate I.) covers the sclera and sends prolongations (*check ligaments*, Plate I.) to the walls of the orbit, thus retaining the eyeball in its proper position. The intimate connection between Tenon's capsule and the muscular sheaths is of prime importance in the operation of tenotomy, since it is because of this connection that the cut-end of the muscle is prevented from excessive retraction until a new union with the sclera takes place.

The third (oculomotor) nerve supplies all the muscles of the eyeball except the superior oblique and the external rectus. The superior oblique is supplied by the fourth and the external rectus by the sixth nerve. The nuclei of all three of these nerves lie in the floor of the fourth ventricle, in the order (from before backward) in which they are numbered.

The eyeball is freely movable in all directions, the centre of rotation being slightly behind the geometrical centre (p. 143). The movements which may be imparted by the muscular apparatus are: (1) Around the vertical axis, *adduction* (toward the nose) and *abduction* (toward the temple); (2) around the transverse axis, *elevation* and *depression*; (3) around the antero-posterior axis, *torsion*, in which the corneal meridians rotate from right to left or from left to right. Two or more of these movements may be simultaneously combined.

The functions of the internal and external recti are confined respectively to the production of adduction and abduction; the actions of the other muscles vary with the position of the eye. Thus the chief purpose of the superior rectus is to turn the cornea upward (elevation), but, owing to the divergence of the orbits, when the eye is directed straight forward (*the primary position*) the superior rectus will also assist in adduction and will produce an inward rotation of the upper extremity of the vertical axis (Fig. 51). If the eye has been

adducted by contraction of the internal rectus, the adducting and rotatory power of the superior rectus is increased; but if abduction is present, these secondary actions of the superior rectus are diminished, vanishing when the antero-posterior diameter lies in a straight line with the meridian of muscular action; in still greater abduction secondary actions, opposite to those described, must arise. Similarly, to the depressant action of the inferior rectus is added adduction and rotation outward of the upper extremity of the vertical axis, except when the eye is in a state of abduction equal to or greater than the angle which the inferior rectus makes with the antero-posterior axis, the average size of this angle being about 23° (Fuchs).

The superior oblique muscle moves the cornea downward and outward, and rotates the upper end of the vertical axis inward. The last of these motions is greater when the eye is in abduction, diminishing or even vanishing when the eye is in a state of strong adduction.

The inferior oblique moves the cornea upward and outward, and rotates the upper end of the vertical axis outward, the last action being greatest in abduction and least in adduction.

An important function of the two oblique muscles is to keep the eyeball from being drawn backward into the orbit during contraction of the straight muscles; being thus properly poised, the eye rotates freely about its centre without displacement.

Field of Fixation.—This corresponds to the rotatory power of the ocular muscles; it is measured by the maximum angle which the visual line makes with the primary antero-posterior axis. This angle (for the normal eye) is about 47° in all directions (Landolt). Some authorities give a higher degree of downward rotation (50° or 60°).

BINOCULAR FIXATION.

Binocular vision consists in the fusion into a single mental perception of the two images as formed in the two eyes. There is a slight dissimilarity in these two images because of the difference in position of the eyes. It has been estimated (Helmholtz) that the mind is capable of perceiving a difference in the two images (when viewed monocularly) for distances not exceeding 240 metres.[1] By means of this difference in the two images and also through the aid of a number of psychic influences which cannot be considered here, the mind is enabled to estimate distances and solidity; that is, it visually perceives the three dimensions of space, notwithstanding the fact that the retinal image is a surface-image.

The fusion of the two images in binocular vision is possible only when the image of direct vision falls upon the fovea centralis of each eye; in other words, the lines of vision of the two eyes must converge to the point of fixation. This is accomplished throughout the field of binocular fixation by delicately adjusted associations of muscular action. The field of binocular fixation is about 47° in all directions except infero-laterally, where it is limited by the prominence of the nose (Landolt).

Conjugate Movements.

When a person wishes to look at an object situated off the median plane, as to the right or to the left, he avoids unnecessary movements of the head by turning both eyes to the right or to the left, according to the position of the object. This is accomplished by abduction of one eye associated with adduction of the other. The simultaneous contraction of the external rectus of

[1] This is based upon the experimental observation that a difference of 1 min. of arc can be discerned. Phys. Optik., p. 644.

one eye and of the internal rectus of the other eye can be explained only on the assumption that there exists in the brain a connection between the visual centres and a certain other centre or nucleus, which in turn has nerve connections with the external rectus of one eye and with the internal rectus of the other. In addition to these connections, the impulse for lateral deviation must also be transmitted through nerve connections to the other ocular muscles, since these all have a secondary, but very important function in the execution of lateral movement. So fixed is this association of action that it is impossible to turn one eye to the right or to the left without a corresponding movement of the other eye.

Similarly, depression or elevation of one eye is always accompanied by a corresponding depression or elevation of the other eye.

Convergence.

The conjugate movements must in every case be associated with the proper convergence of the visual lines so that the latter may meet at the point of fixation. Convergence is effected by the simultaneous contraction of both internal recti, in conjunction with appropriate contraction or relaxation of the other ocular muscles. For the accomplishment of this united action, there must be a connection between the visual centres and a centre (convergence-centre), which in turn must have nerve connections with both internal recti, and also secondarily with the nuclei of the other ocular muscles.

The greater degrees of convergence are usually associated with downward rotation of the eyes, as in reading; on this account convergence for a near object is accomplished with much less fatigue when the object is below than when it is above the eyes.

Measurement of Convergence.—The degree of convergence is measured by the angle through which each

eye must turn from parallelism of the visual lines in order to converge to the point of fixation. This angle may be measured in degrees, but it is found more convenient to express it in terms of the *metre-angle* (Nagel). A metre-angle is that angle through which each eye must turn from the primary position (parallelism) in order to converge to a point at a distance of 1 metre. Similarly, the angle through which each eye must turn in order to converge to a point $\frac{1}{2}$ metre distant would be expressed by 2 metre-angles, and so on. This system possesses the advantage that in emmetropia the convergence, as thus measured, is equal to the accommodation as expressed in dioptres. When an emmetrope looks at a distant object he requires no accommodation and no convergence; when he looks at an object distant 1 metre he exercises 1 D. of accommodation and 1 ma. of convergence, and so on.

The only objection to this unit is that it has no fixed value, since the value varies with the distance between the two eyes. This distance ranges from 50 mm. to 75 mm., and it is found by calculation that the metre-angle has a value of 1.43 degrees in the former and of 2.15 degrees in the latter case. The average interocular distance is about 64 mm. (Nagel) in the adult, and for this distance the metre-angle has a value of 1.83 degrees. This corresponds approximately to the deviation produced by a prism having a power of $3\frac{1}{2}$ prism-dioptres. Hence, using this average as a standard, 1 ma. of convergence is equivalent to the effect of a prism of $3\frac{1}{2}^{\triangle}$, base out, before each eye, or of $7^{\triangle}$ before one eye.

Near-point of Convergence.—This is the nearest point for which convergence can be made. Landolt places it for the normal eye at a distance of $\frac{1}{9.5}$ metre (10.5 cm., or approximately 4 inches), representing a converging power of 9.5 ma.

It is not possible, however, for one to use this amount

of convergence continuously, just as it is not possible to exert the maximum accommodative effort for any length of time; but whereas two-thirds of the accommodative power can be continuously employed, only *one-third* of the converging power is available for continuous use; that is, the nearest point for which comfortable convergence can be maintained is about 30 cm. (12 inches).

Relaxation of Convergence (Divergence).—Relaxation of accommodation is accomplished by the inherent properties of the crystalline lens when released from the traction of the ciliary ligament; but convergence, being opposed by the external recti, can be properly relaxed only by the innervation of these diverging muscles, with a simultaneous relaxation of the converging muscles. This implies that there must be a nerve-centre for divergence as well as for convergence, the two centres being intimately associated.

Far-point of Convergence.—In man, who possesses binocular vision, absolute divergence of the visual lines can never exist as a normal condition, parallelism (no convergence and no divergence) being required for very distant objects. But it does not follow that the far-point of convergence lies at infinity, for it can be shown by the interposition of a prism that normally it is possible to produce a slight divergence of the visual lines, in which case the latter meet behind the eyes. The divergence being expressed as negative convergence, the far-point is negatively situated behind the eyes. The negative range of convergence is normally about 1 ma. (Landolt), this being manifested by placing before one eye (or before both eyes) a prism whose base is directed toward the nose. The strongest prism with which a distant object (a small light) is seen singly represents the diverging power. A divergence of 1 ma. is obtained by a prism of $3\frac{1}{2}^{\triangle}$, base in, *before each eye*, or by a prism of $7^{\triangle}$ before one eye.

Association of Accommodation and Convergence.—In normal vision every change in convergence is accompanied by a corresponding change in accommodation. In emmetropia vision at 1 metre is accomplished with 1 D. of accommodation and 1 ma. of convergence; at $\frac{1}{3}$ metre there must be exercised 3 D. of accommodation and 3 ma. of convergence, and so on. So intimate is this association between these two functions that exercise of one of them is involuntarily accompanied by a corresponding action of the other.

Although normally associated, accommodation and convergence are not indissolubly connected; with exercise of a fixed degree of convergence the amount of accommodation may, within certain limits, be varied, and *vice versa*. If a weak concave lens is placed before each eye of an emmetrope, he can still see a distant object clearly by exercise of accommodation while the convergence (parallelism) remains unchanged; but when the strength of the concave lenses is increased beyond a certain limit, either the object will appear indistinct from insufficient accommodation or diplopia will result from excessive convergence. The limit of accommodation with parallelism of the visual lines is slightly more than 3 D. (Donders) for an emmetrope twenty years of age.

The addition of a convex lens to each eye in emmetropia would render a distant object indistinct, since no further relaxation of accommodation is possible; but if a near object is viewed, the accommodation may, within certain limits, be increased by concave lenses and diminished by convex lenses, while the convergence remains unchanged. In vision at 33 cm., the requisite convergence being 3 ma., accommodation may be varied from 0.5 D. (by convex lenses) to 6.5 D. (by concave lenses) in an emmetrope twenty years of age (Donders).

The difference between the least and the greatest amount of accommodation that is possible with a fixed

convergence constitutes the *relative range of accommodation.* This varies not only in different individuals; it varies also with the degree of convergence, with the amplitude of accommodation (that is, with the age), and with the refractive condition.

As the accommodation can be varied while convergence is unaltered, so the convergence may, within certain limits, be increased or diminished without change of accommodation. This has already been shown in connection with the diverging power of the eyes; it is possible to produce by means of prisms (bases in) a divergence (negative convergence) of 1 ma. when the accommodation is completely relaxed. It is also possible to produce by means of prisms (bases out) a convergence of about 2 ma. (7$^{\triangle}$ prism before each eye) without exercise of accommodation.[1] With 3 D. of accommodation convergence may vary from zero (parallelism) to about 6 ma. The difference between the least and greatest convergence with a fixed amount of accommodation represents the *relative range of convergence.*

This latitude in the relative accommodation and convergence is of great importance, for it is through this variation that comfortable binocular vision is frequently possible in ametropia, and that the accustomed relation in ametropia may be disturbed by correcting lenses with at least only temporary discomfort.

NORMAL MUSCULAR EQUILIBRIUM.

In a state of complete repose the directions of the visual lines are determined by the relative lengths of the extra-ocular muscles when these are all in complete

[1] Convergence of 3 ma. or more (7 ma. according to Stevens) may be produced while a small light is still seen singly at 6 metres, but accommodation is not excluded in this case; if test letters are used, normal vision cannot be maintained with so great an amount of convergence.

relaxation. Entire absence of innervation of these muscles exists, however, only during closure of the lids, in sleep (natural or narcotic), in blindness, and after death. Examinations show that under these conditions the eyes usually assume more or less divergence in accordance with the divergence of the orbits, which would give in man, as in lower animals, a natural divergence of the eyes, if this tendency were not overcome by the capacity for binocular single vision.

But since complete muscular relaxation does not occur in physiological vision, the effect of such relaxation upon the directions of the visual lines is of minor importance. The vital question is that of the position of equilibrium of the ocular muscles during vision. In distant emmetropic vision no accommodation is required and the visual lines must be parallel; convergence must be exactly neutralized by the external recti, and the vertical adjustment (controlled chiefly by the superior and inferior recti) must exactly correspond in the two eyes. If the relation between accommodation and the extra-ocular muscles is perfectly adjusted, the eyes will assume the proper position for binocular single vision, even though one eye may be excluded from vision.[1] This is the ideal (normal) muscular equilibrium; it may be called *orthophoria* (Stevens).

Similarly, in orthophoric near vision the requisite accommodation will be accompanied by suitable convergence for binocular single vision, even though one eye may be excluded.

On the other hand, binocular single vision may be habitually performed, either with or without discomfort, and yet when one eye is excluded from vision it will involuntarily move inward (*esophoria*) or outward (*exophoria*), or upward or downward (*right* or *left hyperphoria*). This shows that although the proper

[1] The methods of determining the muscular balance are given in Chap. XVII.

convergence of the visual lines can be maintained for binocular vision, yet this direction is not the position of equilibrium which is imparted by the extra-ocular muscles in response to stimulation received from the accommodation centre. Any such deviation from the condition of orthophoria is called *heterophoria*.

While orthophoria is the ideal condition, slight heterophoria is not to be regarded as necessarily constituting an anomaly; for if the proper convergence can be maintained without strain during vision, it is immaterial whether the convergence may be deficient or excessive when the appropriate centres are not directly stimulated by the desire for binocular single vision.

PART III.

ERRORS OF REFRACTION.

CHAPTER XI.

THE METHODS OF DETERMINING THE REFRACTION OF AN EYE.

The various methods which are at our command for determining the refractive condition of an eye may be divided into two general classes: (1) *Subjective* methods, which depend upon the statements of the individual under examination, and (2) *objective* methods, in which these statements play no part, the examiner relying solely upon his own judgment. The determination of refraction is called *optometry*, and any instrument used for this purpose is an *optometer*.

SUBJECTIVE METHODS.

Optometers Based upon the Action of a Convex Lens.—A single convex spherical lens placed before the eye constitutes the simplest of optometers. We know that if the distance from the lens to an object is greater than the focal length of the lens, rays from the object will enter the eye in convergent pencils, and, consequently, will be focused on the retina only when

the eye is *hyperopic*. If the distance from the lens to the object is equal to the focal length of the lens, the rays from any point of the object will be parallel when they enter the eye, and will be focused on the retina of an *emmetropic* eye; and if the distance between the object and the lens is less than the focal length of the lens, rays from any point of the object will enter the eye in divergent pencils, and can be focused on the retina only when the eye is *myopic* or exercising accommodation. Hence, if the object is so small that it cannot be distinguished unless its image is accurately formed on the retina, we are enabled to judge by the position of the lens whether an eye is hyperopic, emmetropic, or myopic. Many of the older optometers were constructed upon this principle, variation being made in the strength of the lens and in the manner of mounting.

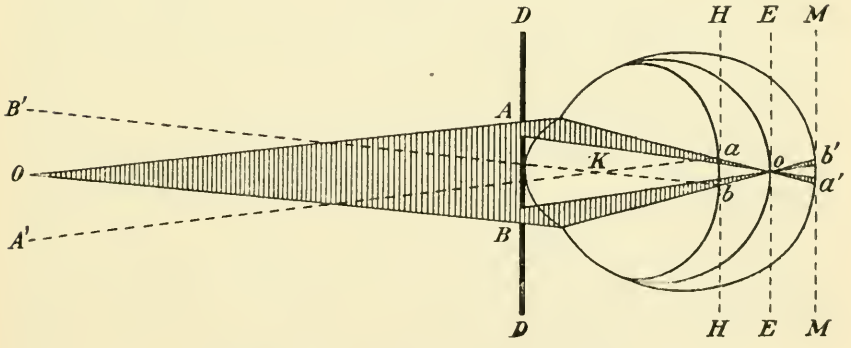
All optometers of this kind have two serious disadvantages: (1) The magnifying power of the lens varies with every variation in the position of the lens and of the test-object; (2) an untrained eye frequently finds difficulty in looking at a near object without exercise of accommodation, thereby rendering the result of the examination uncertain.

Optometers Based upon the Principle of the Opera Glass or Galileo's Telescope.—Optometers of this kind consist of a combination of a strong concave lens, or *eye-piece*, with a weaker convex lens, or *objective*. By varying the distance between the two lenses different refractive effects are produced. If the two lenses are in contact, the effect of the concave lens, which is the stronger, predominates, and the combination is equivalent to a concave lens whose strength is equal to the difference in power between the two lenses; but as the convex lens is withdrawn from the eye its refractive effect increases, and in a certain position the two lenses exactly neutralize each other. By further withdrawal of the convex lens the combination finally

becomes equal to a convex lens. Hence, according as a distant object appears distinct to the eye under examination when the combination is equivalent to a *convex*, *plane*, or *concave* lens, the eye is *hyperopic*, *emmetropic*, or *myopic*, and from a suitably constructed scale the degree of ametropia can be determined. But this test, like the preceding one, lacks accuracy because the magnifying power of the convex lens increases rapidly as it is withdrawn from the eye.

Optometers Based upon Scheiner's Experiment. —When one looks through minute openings at a small object placed at a distance for which the eye is not adapted, the object appears multiplied, each opening furnishing a separate image. This phenomenon is called, from its discoverer, *Scheiner's experiment*. Let *O*, Fig. 52, represent a point of light, *D D* the diaphragm,

FIG. 52.



Scheiner's experiment. (From Landolt.)

and *A* and *B* the openings. If *o* is conjugate to *O*, and if the retina intersects the axis at *o*, there will be a single image of the point *O*; but if the retina lies in front of *o*, the light passing through the opening *A* will fall upon the retina at *a* and that passing through *B* will fall upon *b*. The light which falls upon the retina at *a* will appear to proceed from *A'*, since in ordinary vision light from *A'* would fall upon the retina at *a*.

Similarly, the light which passes through B and falls upon the retina at b will appear to proceed from B'. If a red glass is placed at the opening A, the red light will appear below and the untinted light will appear above; in other words, the relative position of the two lights will be inverted. But if the retina lies behind o, the image a' will be below and b' will be above, and in projecting these images externally through the nodal point of the eye the relative position of the two lights will be the same as in the diaphragm. The point of light may be represented by a small flame distant 6 metres from the eye. When a single image is seen, the eye is *emmetropic;* when two images are seen, the relative position being opposite to that of the openings in the diaphragm, the eye is *hyperopic;* and when the relative position of the two images is the same as that of the openings, the eye is *myopic*. By placing a suitable lens in front of the eye the two images may be united and the degree of ametropia estimated. Upon this principle optometers were constructed by Thomas Young, Porterfield, and others.

Optometers Based upon the Property of Chromatic Aberration.—In the application of this property a small flame is placed five or six metres from the eye undergoing examination, the flame being covered with cobalt blue (purple) glass, which allows both blue and red light to pass through it. The blue rays, being more strongly refracted than the red rays, are brought to a focus sooner than the red. If the blue rays are focused slightly in front of the retina and the red rays slightly behind it, the image of a point of light will be a small diffusion circle, in which both red and blue light will be present, and the point will be seen as a small purple spot. This is the condition in *emmetropia*. If the eye is *hyperopic*, neither the red nor the blue rays will be focused on the retina, but the blue will be nearer its focus than the red light. Hence,

there will be formed on the retina a diffusion circle, the central part of which will contain both blue and red rays, but more blue than red, and the outer part will contain only red rays; the image will, therefore, appear as a *central blue area* surrounded by a *red band.* On the other hand, in *myopia* both red and blue rays will have passed their foci before reaching the retina, and the blue will be more diffused than the red light. Hence, the central part of the diffusion circle will contain mostly red and the outer part only blue light; the image will, therefore, appear as a *central area of red* surrounded by a band of *blue* light. The degree of ametropia may be ascertained by placing before the eye such a lens as will render the image uniformly purple throughout. This lens is the measure of the ametropia.

Optometers Based upon the Measurement of the Retinal Diffusion Circles.—Two distant points of light separated by a sufficient interval will appear separate and distinct to the emmetrope; but to the ametrope the points will appear as two bright disks whose size will increase with the degree of ametropia. If the diffusion circles are sufficiently large, these disks will appear to overlap, and the distance between the two lights must be increased in order that the images may be entirely separated. From a suitably constructed scale the degree of ametropia may be estimated by observing the least distance which may intervene between the two lights while they are seen as separate. Thomson's ametrometer is based upon this principle.

Optometry Based upon Movement of the Diffusion Image on the Retina.—If one looks at a distant point of light through a stenopæic slit which is moved from side to side, he sees an apparent movement of the light except when his eye is so adapted as to focus the light on his retina. This is apparent from Fig. 52, in which *A* may represent the first position of the stenopæic opening and *B* the position into which it is

subsequently moved. If the eye is hyperopic, the retinal image of O will fall at a in the first position, and as the slit is moved to B the image will move to b. If the eye is adapted for the point O, the image remains at o in all positions of the slit. If the eye is myopic, the image moves from a' to b' when the slit moves from A to B. Hence, if O is a distant light the eye is hyperopic or myopic according as movement of the slit causes an opposite or a like displacement of the light. The lens which neutralizes the displacement measures the ametropia. This test, under the name of *kinescopy*, has recently been introduced by Holth.[1]

Optometry Based upon Visual Acuteness.—Scheiner's experiment, the chromatic aberration test, and kinescopy are useful in certain cases, as in defective vision and in simulation, but for general use the one subjective method which is indispensable consists in the testing of the visual acuteness with the aid of trial lenses.

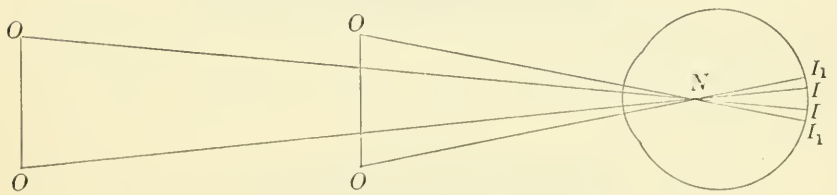
Visual acuteness is measured by the least interval which may exist between two points while they are still distinguished as separate. It is apparent that this interval, as measured on the retina, cannot be less than the diameter of one sentient element of this organ; for when two adjacent elements are illuminated no interval of darkness can exist between the two points. The interval between retinal cones in the macular region is probably about 0.002 mm., and this length subtends, at the second nodal point, an angle somewhat less than one-half minute. Since an object subtends at the nodal point the same angle which the image subtends at this point (Fig. 53), we should expect the *minimum visual angle* for distinguishing points to be about one-half minute; but, because of the imperfections of the eye, it is found that even under favorable circumstances it is rarely possible to distinguish points separated by so small an interval.

[1] Ann. d'ocul., vol. cxxviii. p. 241.

The astronomer Hooke, in 1705, made the first investigations to ascertain the minimum visual angle. Taking the multiple stars as the points, he found that in no case could any interval be distinguished when the angle was less than one-half minute, and in most cases an angle of one minute was required in order that the interval could be distinguished.

For practical purposes a series of parallel lines affords a more convenient means of testing visual acuteness. The least angle which, under favorable circumstances, may separate black lines on a white ground while the interval between them is perceived is about 50 seconds.

FIG. 53.



The visual angle.

If *O O* represents the linear dimension of an object, the image of this dimension will be represented by *I I* or $I_1 I_1$, according to the situation of the object. Conversely, the image *I I* may correspond to an object of any size, provided the object is so placed as to subtend at *N* a visual angle equal to *I N I*. (The two nodal points are merged in a single point at N.)

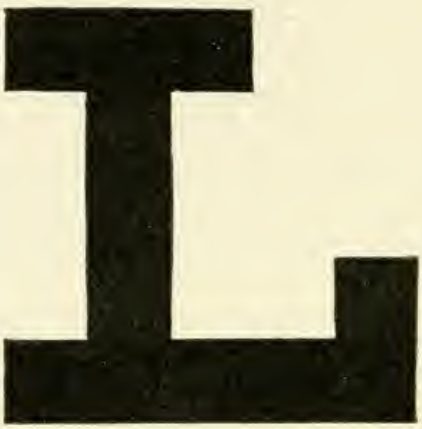
This angle corresponds to a linear distance on the retina of slightly more than 0.004 mm. ; that is, it is more than twice the diameter of one retinal cone.

In accordance with these facts, Snellen, in 1862, constructed a series of test-letters (*optotype*) for the examination of visual acuteness. The whole letter in each case is made to subtend an angle of 5 minutes when in the proper position, and each stroke of the letter subtends an angle of 1 minute (Fig. 54).

Since some eyes do not have the normal visual acuteness, it is convenient to have letters of different sizes, the distance at which the letters subtend an angle of 5

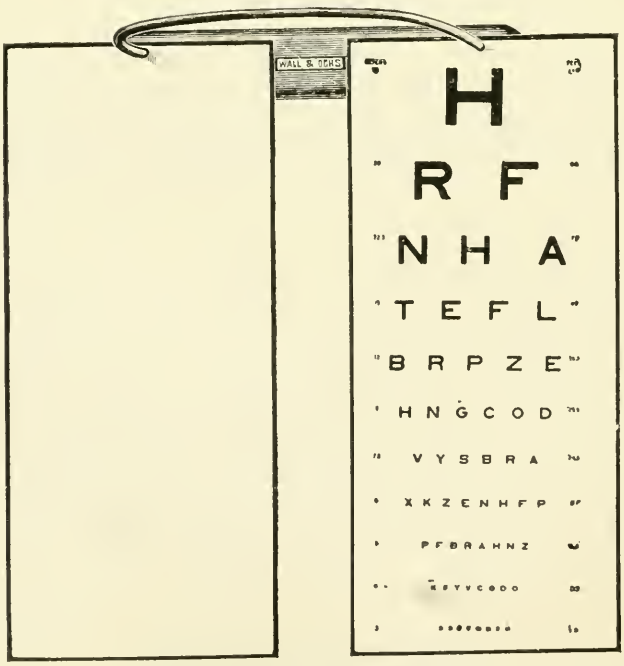
minutes being denoted for the letters of each separate size (Fig. 55).

Fig. 54.



When placed at a distance of 30 metres the breadth of each stroke of the letter subtends an angle of 1 minute at the nodal point of the eye; each dimension of the whole letter subtends an angle of 5 minutes.

Fig. 55.



Thorington bracket with test-letters.

In order to facilitate relaxation of the accommodation the letters are arranged so that they may be placed at a distance of 5 or, preferably, 6 metres from the eye undergoing examination.

If the distance is 6 metres and if the individual can read those letters which subtend a visual angle of 5 minutes, the eye possesses *normal visual acuity.* This is recorded thus: $V = \frac{6}{6}$ or $V = 1$. But if at this distance the individual can read no smaller letters than those which should be read at 9 metres, the visual acuteness is recorded by the expression $V = \frac{6}{9}$.[1] The *distance at which the examination is conducted is the numerator,* and the distance at which the smallest distinguishable letters *should be read* is the *denominator* of the fraction expressing the visual acuteness.

We have seen that the minimum visual angle is somewhat smaller than that required for normal ($V = 6/6$) vision as indicated by Snellen's test-letters; moreover, it is not necessary for one to see distinctly all the lines of a letter with which he is familiar in order to read the letter correctly. It not infrequently happens, therefore, that one can read at a distance of 6 metres the letters which subtend the 5-minute angle at 4 metres, or even at 3 metres, and we may thus have $V = \frac{6}{4}$ or $V = \frac{6}{3}$. It is, in fact, the rule in young persons to find a visual acuteness exceeding the normal as indicated by the test-letters. After middle age the visual power undergoes a diminution and vision exceeding $\frac{6}{6}$ does not so often occur.

Because visual acuteness so frequently surpasses the standard fixed by Snellen, his plan has been modified by the substitution of a 4-minute angle. Nothing is gained by this substitution of a standard, which, while more accurate for the young, is too high for middle and

[1] The method sometimes adopted of expressing the visual acuteness as a decimal fraction has the disadvantage of not indicating the distance at which the test has been made.

old age. The *average normal visual acuteness* is sufficiently approximated by Snellen's 5-minute-angle standard, and any alteration, unless universally adopted, can only lead to confusion.

Of the other modifications of Snellen's optotype, it suffices to mention that of Landolt, who has substituted for the alphabetical characters a circle having an opening in its circumference (O). The size of the hiatus conforms to the minimum visual angle of Snellen. The character is varied by placing the hiatus in different positions. This plan has a number of advantages, from a scientific point of view, over the use of letters; yet, because of the convenience of the latter, it is probable that they will continue in common use. Landolt's charts are, however, especially convenient for illiterates.

Since some persons very soon memorize the test-letters, it is well to have a number of test-cards, and in the selection of these it is of prime importance to have all the cards uniform in respect to the size and distinctness of the letters which are to be read at the specified distance.

In making use of this method of examination care must be taken to provide sufficient illumination. If daylight is used, the card should be so placed that the light from the windows does not shine directly into the eyes of the person under examination. If sufficient daylight is not available, gas or electric light may be used, proper shades being employed, so that the direct rays from the lamp will not reach the eyes.

Each eye should be tested separately and the eye not undergoing examination should be excluded by an opaque disk.

When it is desired merely to test the visual power without the aid of lenses, all that is necessary is to place the individual and test-card in proper position and observe the smallest letters which can be read. The distance at which they are read divided by the dis-

tance at which they ought to be read expresses the visual power.

But when our object is to discover the refractive condition of the eye, we must select and place before the eye that lens which produces best vision. Furthermore, since we wish to compare the visual acuity with that of a normal emmetropic eye, we must endeavor so to place the lens that the retinal image will be of the same size as that of the emmetropic eye. We have learned that in axial ametropia a lens placed at the anterior focus of the eye (about 14 mm. from the cornea) renders the retinal image of the same size as that in emmetropia; but that in curvature ametropia, as in astigmatism, normal images can only be secured by placing the lens in contact with the cornea. It is seldom possible to wear the lens nearer than 15 mm. from the cornea, and the slight magnifying or minifying effect thus produced is neglected.

The lens which, when placed in proper position, affords the maximum visual power measures the ametropia, for it is evident that the highest power of vision will be obtained when the image is accurately focused on the retina.

Trial Lenses.—In order to facilitate the selection of the proper lens, the examiner must be provided with a case of trial lenses. This consists of pairs of convex and concave spherical and cylindrical lenses, prisms, plane and colored glasses, opaque disks, stenopæic disks, trial frames for holding the lenses before the eye, and other accessories. In the complete case the interval between lenses is 0.125 D. for those below 2 D. in strength; 0.25 D. for those between 2 D. and 5 D.; 0.50 D. for those between 5 D. and 8 D.; and 1 D. for those between 8 D. and 23 D., the last named being the highest power usually furnished in the case, and this only in the spherical lenses; the cylindrical lenses ordinarily do not exceed 6 D. or 8 D. in strength,

though more elaborate cases are made in which these lenses are supplied up to 16 D.

The dioptric power is marked on each lens, the plus (+) sign being used to denote convex, and the minus (—) sign to denote concave lenses. In cylindrical lenses the dioptric power refers to the power at right angles to the axis of the cylinder. The position of the axis is marked on the glass, and, in order that this position may be determined at a glance, the peripheral part of the lens is usually rough-ground in a direction parallel to the axis.

Determination of the Power and Centre of a Lens.— It is obviously necessary that we should be able to determine quickly the kind and power of any spectacle-lens, and the position of its optical centre. The most common method of ascertaining the power is by *neutralization* with the trial lens of equal denomination, but of opposite sign. If we hold a convex lens in front of the eye and through it look at a distant object, an image of the object more or less blurred will be seen. If the optical centre of the lens lies in the line of vision, no lateral displacement will result; but if the lens is moved laterally, the effect will be that of a prism with its base toward the centre of the lens, and the greater the lateral movement, the greater will be the prismatic effect. Since a prism causes an apparent displacement toward its apex (p. 35), it follows that as the lens is moved to the right the object appears to move to the left, and *vice versa*. On the other hand, if a concave lens is substituted for the convex lens, the object will appear to move in the same direction as the movement of the lens. By selecting from the trial case that lens which annuls this lateral deviation, we have the effect of a plane glass. The lens whose power is sought is of the same denomination but of opposite sign to that which produces this effect.

To determine the position of the centre of the lens, we

view a straight line (as the edge of a test-card) through the lens, and observe the position of the lens in which there is no break in the straight line as seen through the lens and beyond its borders. Marking the points where this line appears to cut the lens, we connect these points by a straight line drawn in ink. This line passes through the centre of the lens. Repeating this process in another meridian, we have two lines passing through the centre, and their point of intersection must indicate the position of this centre.

In a cylindrical lens the lateral deviation takes place at right angles to the axis of the lens, and any line making an oblique angle with this axis undergoes an angular deviation, the explanation of which has already been given (p. 108). Hence, the *direction* of the axis is determined by observing that direction in which a lateral movement of the lens produces no apparent displacement of an object. The *position* of the axis is determined by observing the points at which the unbroken line (as seen through the lens and beyond its edges) cuts the lens ; the straight line joining these points represents the axis of the lens.

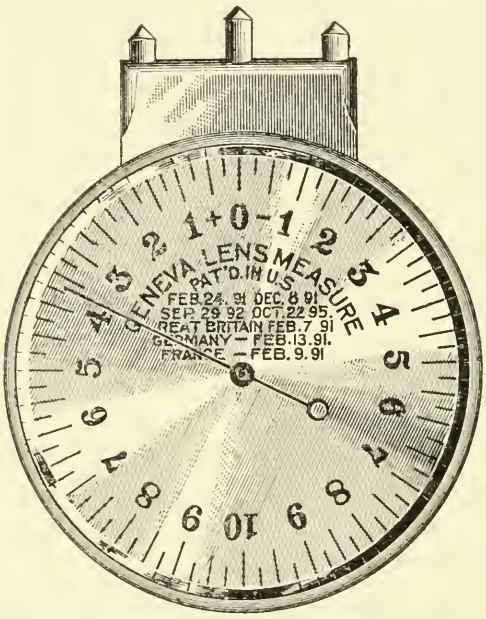
Without resorting to neutralization the power of a lens may be ascertained by direct measurement of the curvature of its surfaces with the aid of a *lens-measure* or spherometer (Fig. 56).

While either of these two methods may be used with satisfaction in ophthalmological practice, each of them may lead to false deduction unless their limitations are appreciated. In the application of neutralization error may occur from neglect of the distance between the optical centres of the two lenses. In the stronger lenses this error is considerable, and for such neutralization is not reliable, except in plano-curved lenses, in which the two curved surfaces may be placed in apposition. In the use of the lens-measure error is liable to occur from the variation which exists in the index of spectacle-glass used

by different manufacturers. Here, also, it is in the high-power lenses that a considerable error is most liable to occur. The strength of high-power lenses is most accurately determined by measurement of their focal length, a stronger convex lens being added to the lens if this is concave.

Cycloplegics.—Being provided with test-letters and trial lenses, we have still another matter for consider-

Fig. 56.



Lens-measure.

ation when we undertake to make use of this method of examination. It is our aim to determine the refraction of the eye with the ciliary muscle in a state of complete relaxation. On this account the letters should be placed not less than 5 metres from the person undergoing examination; but in young subjects even this precaution does not ensure relaxation, and other means must be employed.

Certain drugs possess the property of temporarily paralyzing the action of the ciliary muscle. Since they also dilate the pupil, they were formerly called *mydriatics;* but the discovery of cocain and euphthalmin, which dilate the pupil but do not paralyze the ciliary muscle, has rendered necessary a means of distinction between drugs which simply dilate the pupil (mydriatics) and those which also paralyze the ciliary muscle. The latter are called *cycloplegics.*

The principal cycloplegics are atropin, daturin, hyoscyamin, duboisin, scopolamin, and homatropin. Of these the effect is most persistent in the case of atropin (fifteen days) and most transient in the case of homatropin (from one to two days). Next to homatropin comes scopolamin, whose effect lasts six days, being much diminished in intensity by the second day. Of this list of drugs two, *atropin* and *homatropin*, are sufficient for routine use in the determination of refraction.

The effect of belladonna (from which the alkaloid atropin is derived) upon the pupils and the accommodation has long been known. It is one of the oldest of cycloplegics, having been investigated by Van Swieten more than one hundred years ago. A thorough study of the action of atropin on the accommodation was made by Donders. He found that a single drop of a solution containing 1 part of atropin sulphate to 120 parts of water was sufficient to produce complete mydriasis and complete cycloplegia in a healthy eye. The mydriasis, which occurred first, reached its maximum in about twenty-five minutes, and remained stationary for thirty-six hours, after which it slowly diminished, the pupil regaining its normal size in about fourteen days. The cycloplegic effect was scarcely noticeable until the time of maximum mydriasis, when accommodation rapidly failed, being totally paralyzed at the end of one and a half hours. Total paralysis lasted about forty hours; after this accommodative power gradually returned,

regaining its full amplitude after the expiration of about twelve days.

The weakest solution of which a drop will cause paralysis of accommodation is, according to Jaarsma, 1 : 1200. The duration of this action is twenty-four hours, while the effect on the pupil lasts for ninety-six hours. The same author states that one drop of a solution in the proportion 1 : 80,000 will produce *mydriasis*, the effect lasting twenty-four hours.[1]

Although so small a quantity of the drug suffices to produce its maximum effect in a normal eye, it is advisable to make several instillations before testing the refraction. In this way the tendency to spasmodic contraction of the ciliary muscle, which is so frequently present in young persons, may be overcome. A one-half per cent. solution may be prescribed, and one drop of this should be instilled three or four times a day for two days or longer. By this means constitutional effects of the drug may be avoided and relaxation assured.

If in any case symptoms of poisoning should arise, such as dizziness and dryness of the throat, the strength of the solution must be diminished and special precaution exercised to prevent the solution from entering the nose through the canaliculi. This is accomplished by pressure on the inner canthus at the time of instillation and for a short time afterward.

There sometimes results from the use of atropin the condition known as *atropinism*—an irritation and inflammation of the conjunctiva. It usually occurs only after the prolonged use of the drug in inflammatory states; seldom from the brief use for testing refraction. The cause of this condition is a matter of doubt. It is thought that strongly acid or alkaline reaction of the solution and the presence of micro-organisms are at least contributory elements. Therefore, the solution

[1] Landolt, Refraction and Accommodation of the Eye, p. 564.

should be freshly prepared and, as far as possible, sterile.

Because of the great persistence of the effect of atropin, it is a most inconvenient drug to use in refractive work. It should, therefore, be reserved for those cases in which there is reason to believe that homatropin will be ineffective; that is, for children and for those adults in whom complete relaxation has not followed the use of the latter drug; or, again, for those persons in whom it is desired to produce a prolonged, enforced rest of the accommodation.

Homatropin, as its name implies, is a derivative of atropin, being obtained from the latter through a complicated chemical process. The alkaloid is an oleaginous liquid, which in combination with hydrobromic acid forms a crystallizable salt, and it is this salt that is commonly used in ophthalmological practice.

Complete relaxation of the accommodation may be obtained with homatropin-hydrobromate, except in certain cases of obstinate spasm (such as occasionally occurs in childhood) and in inflammatory conditions. In those cases in which homatropin is applicable for testing the refraction, relaxation may be assured by instilling into the conjunctival sac one or two drops of a 1.5 per cent. solution every ten minutes until six applications have been made. In one hour after the last application the accommodation will be entirely paralyzed. The maximum effect on the accommodation lasts not more than two hours, and at the expiration of twenty-four hours near work may usually be resumed.

A convenient method consists in the application of gelatin disks, as recommended by Dr. Casey Wood. A variety of drugs may be thus incorporated. A suitable combination for the determination of refraction consists of $\frac{1}{50}$ grain of homatropin (alkaloid) and $\frac{1}{50}$ grain of cocain-hydrochlorate. One disk of this composition is sufficient to insure relaxation except in unusual con-

ditions. In children (if atropin should be inadvisable) a second disk should be inserted one hour after the first application. The cocain, though useless alone as a cycloplegic, increases the effect of homatropin and allays the slight irritation caused by the presence of the disk in the conjunctival sac.

Method of Conducting the Test with Trial Lenses.— In making use of the test by trial lenses a preliminary examination is usually conducted without the aid of a cycloplegic. The individual being properly seated, and the other conditions, as described, being fulfilled, he is asked to read the test-letters, beginning with the largest and proceeding to successively smaller letters until he reaches those which he cannot clearly distinguish. If at a distance of 6 metres he can read all the letters which, as indicated on the card, are intended to be read at this distance, vision is normal. This can be the case only if the image of the letters falls accurately upon the retina.[1] The eye must, therefore, be adapted for this distance; that is, there is $\frac{1}{6}$ D. of myopia. But the difference in position of the retina in this amount of myopia and in emmetropia is inappreciable, and we regard the eye as adapted for an infinite distance. The refractive condition, therefore, must be either that of *emmetropia* or of *hyperopia with exercise of accommodation*.

To determine which of these two conditions is present, we place before the eye a convex spherical lens of 0.50 D. If vision is not rendered worse by this lens, it is clear that accommodative action has been replaced by the convergent power of the lens. To ascertain whether accommodation is still being exercised, we add stronger

[1] Strictly speaking, a slight degree of ametropia cannot be excluded until it is proved that a weak lens does not afford still better vision, for, as we have learned, in many cases the acuteness reaches 6/4 or even 6/3.

and stronger lenses until we obtain the strongest which does not render vision worse.

Under favorable circumstances all, or nearly all, the accommodation may thus be replaced by a convex lens, and the dioptric power of this lens is the measure of the hyperopia; but when accommodative tension is great, a portion or, at times, even all the accommodation will remain unrelaxed, and the weakest convex lens renders vision worse. If this condition cannot be otherwise excluded, a cycloplegic must be employed.

If, enforced relaxation being accomplished by cycloplegia, distant vision is still normal without a lens, and is not made to exceed the normal standard by the addition of a lens, the eye is *emmetropic.*

If the vision, having been found normal at the preliminary examination, is below normal after the employment of a cycloplegic, the eye is either hyperopic or astigmatic. If vision is made normal with the aid of a convex spherical lens, this lens measures the hyperopia; but if the spherical lens does not improve vision, or if, while it improves vision, it does not render it normal, astigmatism is present. If this is regular it may be corrected by means of a cylindrical lens.

If vision is below normal without cycloplegia, five conditions are possible : 1. The eye may be hyperopic and without sufficient accommodative power to focus parallel rays upon the retina; if this is so, vision will be rendered normal, or at least improved, by means of a suitable convex spherical lens. 2. The eye may be emmetropic or hyperopic with an excess of accommodative action; that is, the condition simulates myopia, and vision will be rendered worse by a convex lens and improved by a concave lens. 3. There may be true myopia. 4. There may be astigmatism, either alone or in combination with any of the aforementioned defects. 5. The defective vision may be due to no

error of refraction, but to lack of transparency of the media or to anomaly of retina, optic nerve, or brain.

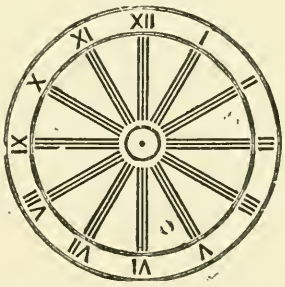
Although we have these five conditions presenting the common symptom of defective distant vision, it is not difficult to make the decision as to which of these conditions exists. In the first case, the fact that a convex spherical lens improves vision reveals hyperopia. In the second case, the condition will be suspected in a young subject and the accommodation paralyzed, when the true condition of hyperopia or emmetropia will appear. In true myopia, as in the previous case, vision is improved by a concave spherical lens. Having excluded, either by cycloplegia or by the age of the individual, spasmodic action of the accommodation, we place before the eye successively stronger concave lenses until we obtain that lens which affords normal or maximum vision. This lens measures the degree of myopia. But as we found it necessary in estimating hyperopia without cycloplegia to select the strongest convex lens, so, under the same condition, we must exercise care to select the *weakest* concave lens which affords maximum vision; for otherwise the myopia will be overestimated, accommodation being exercised to overcome the excessively strong concave lens.

The next and last of the refractive errors to which defective distant vision may be due, is *astigmatism*. We suspect this when neither a convex nor a concave spherical lens affords normal vision. The astigmatism may be regular or irregular. The former occurs, as we have learned, when the cornea approximates in form a torus instead of a sphere, or when the crystalline lens is abnormally inclined to the optic axis. Pathological irregular astigmatism is most frequently the result of corneal inflammation, whereby the regularity of surface has been destroyed. Since this kind of astigmatism cannot be corrected by a lens, its determination cannot be accomplished by the subjective method with which

we are now concerned. Our attention, therefore, is for the present confined to regular astigmatism.

To aid in the detection of the principal meridians of astigmatism, Javal first recommended groups of parallel lines lying in different directions. We know that a straight line appears distinct to an astigmatic eye only when it lies at right angles to the meridian in which it is accurately focused, and that the meridian of greatest distinctness is that in which the refraction needs correction. Hence, if we have groups of equally distinct lines radiating in various directions from a centre, we can ascertain the directions of the principal meridians from the relative distinctness with which the lines are seen. A test-card embodying this principle is illustrated in Fig. 57. It is known as the *clock-face chart*. It is

FIG. 57.



Clock-face chart for the determination of the principal meridians.

intended to be used at a distance of 6 metres, though the breadth of the lines and of the intervals is about twice as great as that required for normal vision at this distance. This has been found to be the most suitable size in the construction of this chart. Other charts for determining the principal meridians are published and may be used if preferred, but their description need not detain us, since in principle they are similar to the clock-face.

The stenopæic disk is an opaque disk, in which there is cut a slit 1 mm. in breadth and 10 mm. in length.

If this is placed before the eye, it allows light to pass into the eye unobstructed in the direction of the length of the slit, while at right angles to this all peripheral rays are excluded. Practically, we may regard all the entering rays as lying in the meridian which corresponds to the length of the slit. Hence, by turning the slit in various directions we can ascertain that meridian in which vision is best. This is the meridian in which the eye is emmetropic or most nearly so.

Returning to the example before us, in which *distant vision is defective and is not made normal by a spherical lens*, we proceed to ascertain whether astigmatism is present. For this purpose we may use the stenopæic disk or we direct the individual to look at the clock-face chart, and to state which group of lines appears most distinct. If none of the lines can be clearly seen, we seek that spherical lens—trying convex lenses first—which makes one group of lines distinct. The group at right angles to this will be the most blurred, if astigmatism is present, and these two groups indicate the directions of the principal meridians, the direction in which the lines are most blurred being that which is corrected by the spherical lens.

In hyperopic astigmatism it is often possible, by exercise of accommodation, to make any group of lines appear distinct. On this account, and also because it is our aim to ascertain, with the astigmatism, the exact static refraction of the eye, a cycloplegic must generally be used in young persons.

Having, with the aid of a cycloplegic if necessary, ascertained the directions of the principal meridians, we place before the eye a weak convex cylindrical lens, its axis being parallel to the group of lines which appears most indistinct. If this lens improves vision and makes the radiating lines more uniform, we replace it by stronger lenses, at the same time shifting the axis slightly, until we find the lens and the position which

afford maximum vision. *All the lines should then be seen with equal distinctness.* If the convex lens renders vision worse, it is replaced by a concave cylindrical lens in the same position; and if this causes an improvement of vision, the lens which affords the maximum vision is selected as just described.

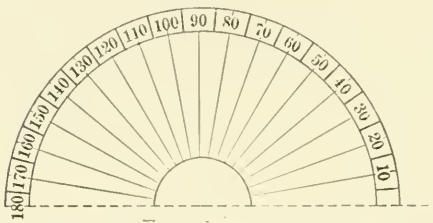
In astigmatism complicated with hyperopia or myopia it is not always easy to determine the exact spherical and cylindrical elements which constitute a perfect correction. Having obtained an approximate correction, we proceed to ascertain whether vision is improved by the addition of a weak convex spherical lens (0.25 D. or 0.50 D.). If this does not cause improvement, we next add a weak convex cylinder, axis parallel to that of the cylinder already before the eye; if this does not improve vision, its axis is turned at right angles to that of the other cylinder. This increases the convexity (or decreases the concavity) of the spherical element while it reduces that of the cylinder. If this also fails to cause improvement, a concave cylinder is next selected and placed first with its axis parallel to that of the lens already found, thus diminishing the convexity of the cylindrical element; if this does not cause improvement, the axis is turned through 90 degrees, whereby the convexity of the spherical element is diminished, while the convexity of the cylinder is increased.[1] If change in the cylinder is indicated by any of these additions the axis of this revised lens must be shifted slightly until the position of maximum vision is obtained. If none of these additions brings vision up to the normal standard, we finally try the experiment[2] of reducing the

[1] The cylindrical changes may be made with the crossed cylinder (Jackson). This consists of a convex cylinder (0.25 D.) combined with an equal concave cylinder, the two axes being at right angles.

[2] The method here described is the "routine of procedure" recommended by Duane (Posey and Wright's Diseases of the Eye, Nose, Throat, and Ear, p. 128). It may be varied somewhat in accordance with individual preferences.

spherical convexity by adding a weak concave spherical lens. If normal vision cannot be obtained by any combination of spherical and cylindrical lenses, we must

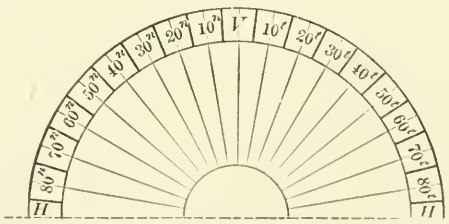
FIG. 58.



Ordinary method of indicating the axis of cylinders or the direction of prisms. In each eye the position of the axis is denoted by the angle which it makes with the horizontal line, this angle being always measured from the right-hand side of the observer (left-hand side of the patient). The numbering thus runs from 0° to 180°, starting at the nasal side in the right eye and at the temporal side in the left eye. The horizontal axis is always denoted by 180°, the vertical axis by 90°. The diagram is for either eye.

conclude that there exists some defect which is incapable of correction by lenses. For the diagnosis of the particular condition which may be present other methods of examination must be employed.

FIG. 59.



Bisymmetrical method of indicating the axis of cylinders. In each eye the position of the axis of the cylinder is denoted by the angle which it makes with the vertical meridian $V (= 0°)$, either on the nasal or on the temporal side, and is written as follows: $5n = 5° n$, $5t = 5° t$, etc., down to $H = 90°$ (horizontal). The diagram is for the left eye; the notation is reversed for the right eye.

If the foregoing examination has been made under artificial cycloplegia, it is advisable to make a re-examination after the influence of the drug has subsided.

Indication of the Axis of a Cylindrical Lens.— The position in which a cylindrical lens is placed is indicated by the angle which its axis makes with a certain fixed line. In America the usual method is in accordance with the notation of angular magnitude as universally employed in mathematical science (Fig. 58). Another system is illustrated in Fig. 59. Knapp recommends for universal adoption a symmetrical system in which the zero line lies horizontally and toward the nose for each eye. The notation is thus the same as in the parallel system (Fig. 58) for the right eye, but the markings run in the opposite direction for the left eye.[1]

OBJECTIVE METHODS.

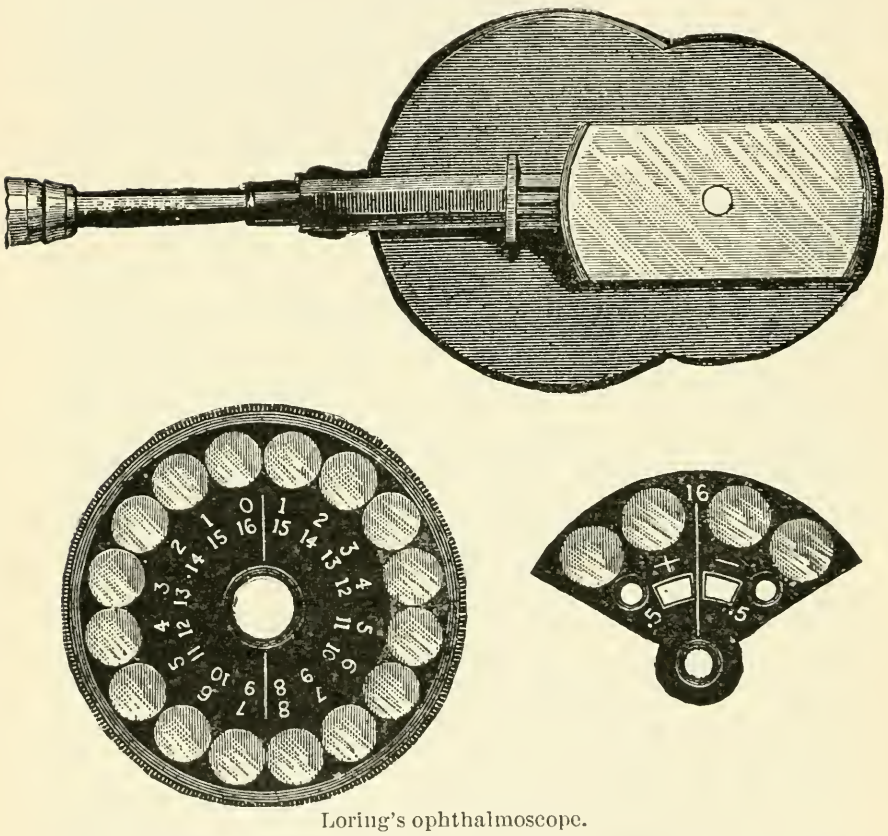
Since our aim in ascertaining the refractive condition is to prescribe suitable lenses, it might seem as if the foregoing method, in which the lenses are actually placed before the eye, would answer all requirements for the selection of glasses; and, in truth, in the final decision as to the proper glass, preference must ordinarily be given to this test. But, owing to the fact that many patients lack intelligence, or purposely mislead the examiner, and to other difficulties, it is of the utmost importance that we should be able to determine the refraction independently of the assertions of the patient.

The first of these objective methods is that in which use is made of the *direct method of ophthalmoscopy.* For conducting this test the examiner must be provided with an ophthalmoscope of at least moderate completeness; that is, the instrument must be equipped with a sufficient number of lenses to enable the examiner to see the fundus clearly, *without any exercise of accommo-*

[1] In order to avoid mistake it is well to have a diagram on the prescription blank indicating the system which is used.

dation, whatever may be the refraction of both examining and examined eyes. The two most popular instruments for general use are Loring's (Fig. 60) and Morton's (Fig. 61).

FIG. 60.

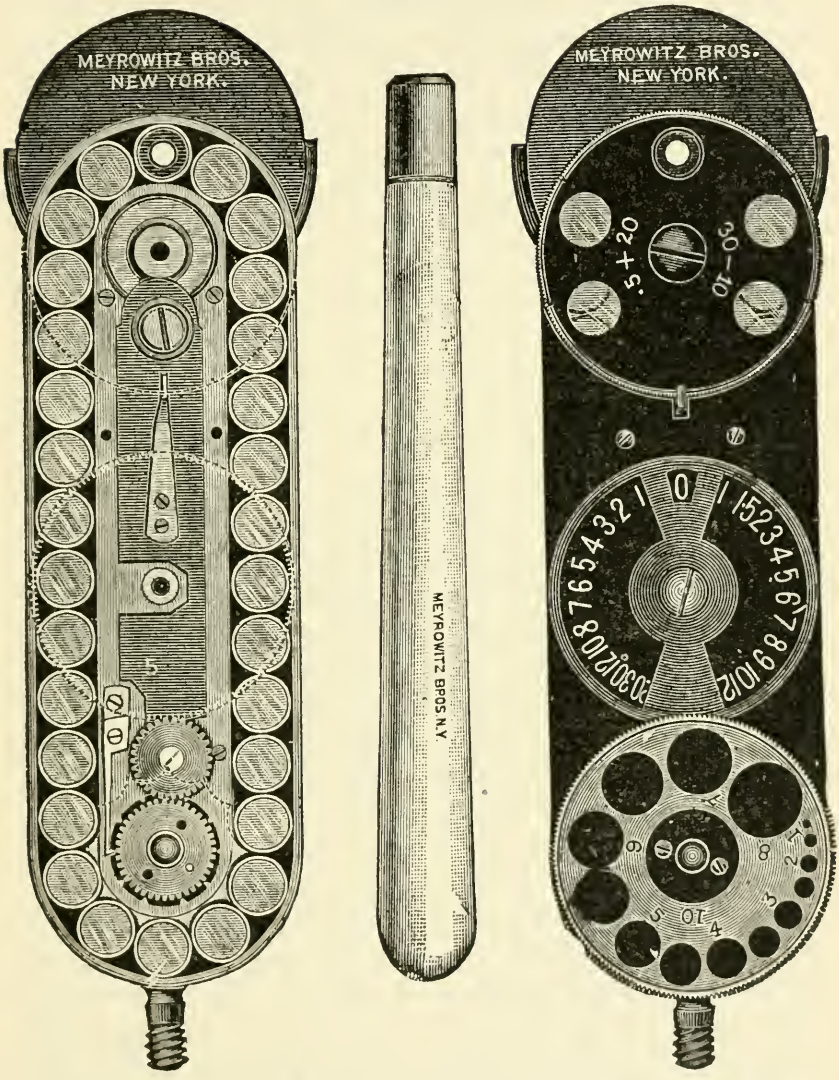


Loring's ophthalmoscope.

The mirror is concave, shaped as in the illustration, with a central perforation of 4 mm. diameter, and so attached that it may be tilted to either side. The focusing lenses are contained in a full disk and a quadrant of a disk, the one revolving over the other, so that by suitable combination any lens required for neutralization of refractive error can be obtained.

In the explanation of the principles of ophthalmoscopy (p. 113) it was shown that light reflected from the fundus of an emmetropic eye will pass out of the eye in parallel rays, which will be brought to a focus

FIG. 61.



Morton's ophthalmoscope.

In this instrument the lenses are set in a cylinder in the form of an endless chain, so that any required lens may be readily brought to the sight hole by means of the driving wheel. In the newest models there are three interchangeable mirrors (on the reverse side of the instrument and consequently not shown in the cut)—one plane and two concave. Of the two concave mirrors one (the larger) has a focal length of about 25 cm. and the other of about 8 cm. The mirror of short focus is more suitable in the direct method, while the weaker concave and the plane mirror are appropriate, respectively, for the indirect examination and skiascopy.

on the retina of an emmetropic observer without exercise of accommodation, thus forming on his retina a clear image of the disk and bloodvessels of the examined eye. If the examined eye is hyperopic, light from its fundus will leave the eye in divergent pencils, and can be focused by an emmetropic observer only by the aid of accommodation, or by an equivalent convex spherical lens. If the examined eye is myopic, the emergent pencils will be convergent, and can be focused on the retina of an emmetropic observer only with the aid of a concave lens.

To apply this principle in practice it is, in the first place, necessary to be assured that no accommodation is exercised by the examining or the examined eye. The examiner must learn by previous practice to relax his accommodation at will; relaxation in the eye under examination usually occurs during ophthalmoscopic examination, provided it is conducted in a thoroughly darkened room.

These conditions being fulfilled, the examiner brings the ophthalmoscope and his eye as near as possible to the eye under examination. The proper position would be such that the ophthalmoscopic lens would be 15 mm. in front of the examined eye—the position at which trial lenses are placed in the subjective examination. Although so close an approximation is not possible, the error is slight except in high ametropia. The examiner now looks at the small vessels which lie on the outer side of the optic disk, tracing them as far as possible toward the macula, *since it is the macular region whose refraction we wish to determine.* The strongest convex or weakest concave lens with which these vessels appear distinct measures the degree of ametropia, provided the examiner is emmetropic. When the latter is ametropic, his refractive error not being corrected by spectacle-lenses, the dioptric power of his correcting lens must be subtracted from that of the ophthalmoscopic lens

with which the vessels appear distinct. Thus, if +5 D. is the strongest lens with which the retinal vessels are seen distinctly and if the examiner has 2 D. of hyperopia, it is evident that 2 D. of the ophthalmoscopic lens is required for the correction of the examiner's hyperopia, leaving 3 D. as the degree of hyperopia in the examined eye. If the examiner has 2 D. of myopia, while, as above, +5 D. is the power of the lens which makes the retinal vessels distinct, the hyperopia of the examined eye is 7 D. Subtracting —2 D., the lens-equivalent of the examiner's myopia is the same as adding +2 D. In other words, the 2 D. of the examiner's myopia neutralizes 2 D. of the hyperopia of the examined eye, and this added to the 5 D. of hyperopia neutralized by the ophthalmoscopic lens, makes a total hyperopia of 7 D. Similarly, if the vessels appear distinct with —5 D., the examiner having 2 D. of myopia, the myopia of the examined eye is 3 D.; and if the examiner has 2 D. of hyperopia, the vessels still being distinct with —5 D., the myopia of the examined eye is 7 D.

When the examiner is considerably astigmatic, it is best to have his correcting lens attached to the ophthalmoscope so that it may be used in combination with the spherical lenses of the instrument.

The same principle is applicable to the determination of astigmatism; but in this case it will be noticed that when the vessels running in a certain direction appear distinct, those running in a direction at right angles to this will be much blurred. *These two directions mark the principal meridians of the astigmatism.* In accordance with the principles which we have learned, we know that the meridian in which the vessels are most blurred is that which is corrected by the ophthalmoscopic lens. After the number of this lens has been noted, the vessels at right angles to the first are next made to appear distinct. The difference between the

power of the first and second lenses represents the degree of astigmatism.

Much practice and skill are requisite for determining accurately the meridians and degree of astigmatism by this method, and, as a practical test for astigmatism, it has been largely replaced by skiascopy and keratometry.

In astigmatism the optic disk, as seen by direct ophthalmoscopy, is elongated in the meridian of greatest refraction. Hence, if we may assume that the actual form of the disk is circular, the astigmatism may be roughly measured by that cylindrical lens, which, when placed as near as possible to the eye, makes the disk appear circular. This method is not, however, sufficiently accurate for practical use.

Indirect Method of Ophthalmoscopy.—Since there is formed at the far-point of a myopic eye an aërial image of the optic disk and retinal vessels, the distance of this image from the eye furnishes a means of determining the degree of myopia. In emmetropic and hyperopic eyes the same method is applicable by adding a strong convex lens, as used in indirect ophthalmoscopy. This method, like many of the older tests, is not convenient in practical work, since it is not possible, without special contrivance, to determine with precison the place at which the aërial image is formed.

In indirect ophthalmoscopy the distortion of the optic disk in astigmatism is opposite to that observed in the direct method, provided the distance of the convex lens from the eye undergoing examination is less than the focal length of the lens.

Skiascopy.—This method is so simple in application and so accurate in results that it surpasses all other objective means of estimating refraction. Bowman, in 1859, first employed skiascopy for the detection of astigmatism and conical cornea; but Cuignet, in 1876, introduced it as a test for all refractive errors under the name *keratoscopie*. As this name implies, Cuignet

was ignorant of the optical principles of the test. The first explanations were given by Landolt, who suggested the name *pupilloscopie*, and by Parent, who adopted the name *retinoscopie*.[1] The latter also introduced the practice of placing the correcting lens in front of the eye, thereby giving the test its practical value in estimating the degree of ametropia. All the earlier names being manifestly unsuitable, Priestley Smith, in 1884, recommended the term *shadow-test*, upon which is based the simple word *skiascopy*.

Many other writers have entered into the study of the theory and practical application of this test, and for its introduction into general use in America we are largely indebted to Swan Burnett and Edward Jackson. To the latter we are indebted also for having added much to our knowledge in regard to the position of the illuminating source.[2]

The necessary appliances for the application of skiascopy are a suitable lamp, a plane or concave mirror, and a set of trial lenses.[3] An Argand gas burner or a frosted electric lamp, mounted on an adjustable bracket gives suitable illumination, or a miniature electric lamp may be attached directly to the instrument. The flame should be covered by an opaque chimney which has a circular opening cut in the side corresponding to the brightest part of the flame. The size of this opening should vary with the position of the light. When this is behind the patient, as is the case in the use of the concave mirror, the opening should be 2 cm. or 3 cm. in diameter; in fact, the opaque shade is in this

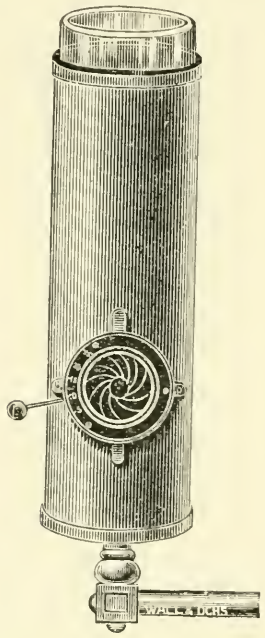
[1] Landolt, Refraction and Accommodation of the Eye, p. 275.

[2] The optical principles upon which skiascopy is based have been presented in Chapter VIII. The student who has mastered these will, with the aid of the information contained in the present chapter, be able intelligently to conduct the test; but for a complete study of skiascopy and for references to the literature of this subject one of the several monographs must be consulted.

[3] A tape-measure for determining the distance between patient and observer is also useful.

case not essential. But when the light is in front of the patient and near the eye of the examiner, this being the most advantageous arrangement in the use of the plane mirror, the shade is indispensable, and the opening should not be more than 10 mm. in diameter. Since it is often desirable to vary the position of the light relatively to the mirror, it is convenient to have

FIG. 62.



Thorington's iris diaphragm-chimney.

a rotating disk, with openings of different sizes, any one of which may be brought before the flame; or the iris-diaphragm may be used, as in Thorington's adjustable diaphragm chimney (Fig. 62).

The *mirror*, being circular in form, should have at its centre a circular sight-hole 2 mm. in diameter; the mirror itself should be from 2 cm. to 3 cm. in diameter if plane, and somewhat larger (3 cm. to 4 cm.) if con-

cave. The focal length of the concave mirror should be about 25 cm.

The *lenses* may be taken from the trial-case, any desired lens being supported in the trial-frame, and placed before the eye undergoing examination; or, they may be arranged in a disk in such manner that any desired lens may be quickly brought before the eye.

The room in which the examination is made should be thoroughly darkened as for ophthalmoscopy, and if the pupil is small, cocain, euphthalmin, or homatropin should be used.

The patient and examiner are seated facing each other as for ophthalmoscopy, the distance between the two being about 1 metre. The patient is instructed to look slightly to the right or left of the examiner's head, according as the right or left eye is under examination, while the examiner throws the light reflected from the flame into the eye of the patient. The examiner then, looking through the sight-hole of the mirror, perceives the light-reflex coming from the region between the optic disk and macula of the examined eye. Examination of the macular region is not possible because of annoying reflexes; but our aim should always be to have this region as little as possible removed from the line of vision, since the refraction of other parts of the eye differs materially from this portion, which alone is concerned in distinct vision.

The manner of estimating the ametropia by this method is best explained by means of illustrative examples. For instance, suppose that with a plane mirror, held 1 metre from the eye under examination, the pupil appears brightly illuminated, and on rotating the mirror the light reflex is followed by a slightly curved shadow which quickly covers the entire pupil; we know that we are near the point of reversal; that is, the eye has *about one dioptre of myopia* (Fig. 63). If the rapidly moving shadow travels in the direction of rotation, the myopia is

slightly less than 1 D.; if it travels in the opposite direction, the myopia is slightly in excess of 1 D. By moving our head forward or backward we may find the position at which no appreciable shadow can be observed, and by measuring this distance from the eye the amount of myopia may be estimated; or by adding a weak lens, convex or concave according as the direction of the shadow is with or against the direction of rotation, we select that which causes the shadow to disappear. The lens which produces this effect in the eye under examination creates an artificial myopia of 1 D. If a convex lens of 0.50 D. is required to produce this result, the eye, having 1 D. of myopia with the lens, must have 0.50 D. of myopia without the lens; if a concave lens of 0.50 D. is required to cause disappearance of the shadow, the eye must have without the lens 1.50 D. of myopia.

FIG. 63. FIG. 64. FIG. 65.

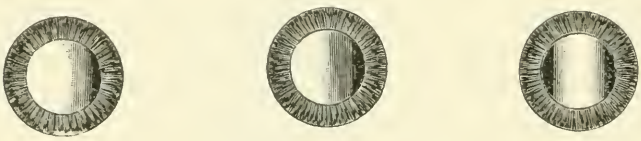


FIG. 63.—Showing the form of the shadow in hyperopia, emmetropia, or myopia.

FIG. 64.—Showing the rectilinear shadow in astigmatism when the examiner, being near the point of reversal of one principal meridian, tilts the mirror to one side.

FIG. 65.—Showing the central band of light in astigmatism.

When, on rotating the mirror in any direction, *the shadow moves slowly across the pupil in the direction of rotation of the mirror*, the reflex being dull, the eye is highly *hyperopic*. We place a 4 D. convex lens before the eye, and note that the shadow moves more rapidly, but still in the direction of rotation. We substitute a convex lens of 6.50 D., and the shadow now moves rapidly in the direction opposite to the rotation. We

therefore take a weaker lens (6 D.) and find that there is now no appreciable shadow; hence, this lens produces 1 D. of myopia, and the eye without the lens must have 5 D. of hyperopia.

If the reflex is dull and moves slowly *in the opposite direction to the rotation*, the eye is highly *myopic*. We may estimate the degree of myopia roughly by moving our eye toward the patient until we reach the point of reversal. If this is $\frac{1}{10}$ metre from the eye, there exists 10 D. of myopia; but as it is difficult to ascertain the exact point of reversal, and as a slight inaccuracy will make a difference of several dioptres in high myopia, it is better to place before the eye a concave lens which will bring the point of reversal to the more convenient position, 1 metre from the eye. At this distance the error resulting from misjudging the exact point of reversal is slight. We, therefore, in this case place before the eye a concave spherical lens of 10 D. and resume our former position, 1 metre from the eye. We notice that the *shadow moves with the rotation;* we substitute a weaker lens (9 D.) and with this the shadow disappears. Since a concave lens of 9 D. neutralizes all but 1 D. of the myopia in this eye, the eye without the lens must have a myopia of 10 D.

The next example is that in which the shadow moves with the rotation in all meridians, but *more rapidly in the vertical than in the horizontal meridian.* By placing a convex spherical lens of 1 D. before the eye the shadow is caused to disappear in the vertical meridian, but in the horizontal meridian the light and shade still travel in the direction of rotation. The edge of the shadow will be straight, or nearly so (Fig. 64), and the direction of this edge *marks the direction of the axis of the cylindrical lens which corrects the astigmatism.* In order that the characteristic appearance may be most clearly displayed for the determination of the direction of the axis of the correcting

lens, the examiner must be at or near the point of reversal of the other principal meridian of the astigmatism (this has been accomplished in our example by the 1 D. lens), and the apparent source of illumination must be as far as possible removed from the point of reversal of this meridian. Hence if, as has been recommended, the lamp has been placed near the mirror, the most favorable conditions are afforded by temporary removal of the lamp to a point behind the patient's head. By suitable adjustment of the mirror the examiner may then see a central band of light bordered on each side by a rectilinear shadow (Fig. 65). The direction of this band indicates the position of the axis of the correcting cylinder. After ascertaining the directions of the principal meridians, the lamp may again be brought near the mirror for the determination of the point of reversal of the horizontal meridian.[1] Having found the edge of the shadow to be vertical, we place a convex cylindrical lens of 2 D., axis vertical, before the eye. With this lens no shadow is noticed in any meridian. Since the convex lens of 1 D. was required to produce 1 D. of myopia in the vertical meridian, the eye is emmetropic in this meridian. In the horizontal meridian the combined action of the spherical and cylindrical lenses is necessary to produce 1 D. of myopia. The combined strength of these two lenses in the horizontal meridian is 3 D.; hence, in this meridian there must be 2 D. of hyperopia without the lenses. The case is one of *simple hyperopic astigmatism* of 2 D.

It is needless to cite further examples illustrating *compound astigmatism* (both principal meridians being hyperopic or both myopic) and *mixed astigmatism* (one principal meridian being hyperopic and the other myopic), since the method of procedure is the same in

[1] These changes in position of the lamp (recommended by Jackson) are not required, except in the lowest grades of astigmatism.

all cases; the point of reversal of one principal meridian is first brought to the position of the examiner with the aid of a spherical lens, and then by the addition of a proper cylindrical lens the other principal meridian is brought to the same position.[1]

The student who has mastered the principles of the test with the plane mirror will have no difficulty in the substitution of the *concave* mirror. As has already been explained, the movement of the light and shadow with the concave mirror is opposite to that with the plane mirror; that is, the motion is *against* the rotation of the mirror in *hyperopia* and *with* this rotation in *myopia*.

Another matter which must be remembered in the substitution of the concave for the plane mirror is, that in the former the apparent source of illumination is the aërial image, situated in front of the mirror, whereas in the latter the apparent source of illumination is behind the mirror. With the concave mirror the aërial image cannot lie nearer the mirror than the principal focus, and with the approach of the lamp to the mirror the aërial image recedes from the mirror.

The ideal arrangement is such that the apparent source of illumination and the observer are at the same distance from the examined eye; and, at any rate, that the relation between these two is constant. With the plane mirror the apparent source of illumination may be brought near the observer by placing the lamp very near the mirror, the observer moving the lamp as he moves his position; or he may have a miniature electric lamp attached to the mirror. Hence, with the *plane mirror* the examiner may vary his position to suit circumstances; he may thus *estimate the ametropia with few changes of lenses*. But when

[1] Or each meridian may be separately corrected by a spherical lens. The difference in power between the two lenses represents the astigmatism.

the *concave mirror* is used, alterations in the illumination of the pupil, due to the variation in position of the aërial image, are so great as to render the test unsatisfactory unless the observer selects a fixed position for himself and lamp. The most suitable arrangement is to place the lamp back of the patient's head while the observer is 1 metre in front of the patient.

Difficulties in the Application of Skiascopy.—Although the phenomena of skiascopy are characteristic, yet when we come to employ this method of examination in practice, we frequently meet with difficulties which arise from imperfections in the optical construction of the eye. The first of these disturbing elements is *aberration*. Since in normal eyes the refracting surfaces are approximately portions of spherical surfaces, the light which passes near the centre of the pupil is less highly refracted than that which passes along the periphery. Hence, when the examiner is at the point of reversal for the central area, he will be within that for the peripheral part of the widely dilated pupil. If the aberration is abnormally great, he may see clearly the shadow at the periphery move in one direction while that at the centre moves in the opposite direction. As the central area is the part concerned in normal vision, the examiner should ascertain the point of reversal for this part of the pupil, disregarding the movement at the periphery.

The aberration just described is ordinary spherical or *positive* aberration; it is the form which usually occurs in the eye. But the opposite or *negative* aberration sometimes occurs. This is the rule in *conical cornea*, for in this condition the curvature of the cornea is much greater at the centre than at the periphery. It was the peculiar effect of aberration in conical cornea that first attracted the attention of Bowman. The observer, being at the point of reversal for the periphery, will be far removed from this point for the centre

of the pupil. Hence, the shadow at the centre will move slowly while that at the periphery will pass rapidly across this part of the pupil, presenting the appearance of the central light area being encircled by the swiftly moving peripheral shadow.

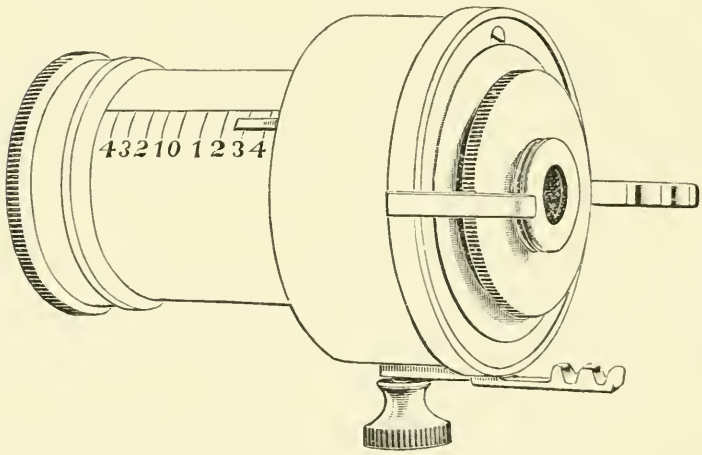
Another difficulty in the application of skiascopy is that which arises from *irregular astigmatism.* This exists, to a certain extent, in all eyes. A careful observation of the shadow when the examiner is near the point of reversal will reveal this by the faint conflicting shadows moving in various directions. When the irregular astigmatism is more pronounced, these shadows are so marked as to interfere seriously with the estimation of the refraction at the centre of the pupil. This is especially so in eyes whose corneas have been the seat of inflammation or ulceration, whereby the regularity of surface has been destroyed. There is no one point of reversal for such eyes, and distinct vision is not obtainable.

A peculiar appearance, described by Jackson as the *scissors movement,* is sometimes seen.[1] This happens when in a certain meridian one part of the pupil is more myopic than another part; thus, if the examiner is within the point of reversal for the upper part of the pupil and without this point for the lower part, rotation of the mirror will cause the two shadows to move toward or away from the centre of the pupil. Since the appearance resembles the opening and shutting of a pair of scissors, it has received therefrom its name. This phenomenon indicates imperfect centring of the cornea or lens—a defect which produces regular as well as irregular astigmatism. The regular astigmatism will be indicated by a central band of light, and by ascertaining the points of reversal for this central area the correcting lens may be determined.

[1] Jackson, Skiascopy, p. 66. Edwards & Docker.

In order to obtain a clear conception of these various appearances and to obtain the requisite skill for the practical application of skiascopy, the student should procure an *artificial eye* (Fig. 66), constructed for this purpose, and thoroughly familiarize himself with the phenomena which are to be observed in various grades of ametropia. Having accomplished this, he is prepared to make further studies upon living eyes, selecting at first those which are free from marked irregularities. He should, if possible, conduct the examination with a

FIG. 66.



Veasey's eye model for the practice of ophthalmoscopy and skiascopy.

moderately dilated pupil, thus avoiding the aberration and irregular astigmatism so commonly present at the periphery when the pupil is widely dilated.

Keratometry.—The simplest contrivance for determining the form of the cornea is that known as Placido's disk. This is a metal disk having a sight-hole at its centre and having on its face concentric circular rings, alternately black and white. If the cornea is spherical, the image of these rings, as seen reflected from the cornea, will be circular; if the cornea resembles

a torus the image will have a greater diameter in the meridian of least curvature than in that of greatest curvature, and the rings will appear elliptical; while if the cornea is irregular, the image of the rings will be irregularly distorted. In this way it is possible to determine roughly the presence of regular or irregular astigmatism.

But for the application of this principle to the accurate estimation of the degree of astigmatism, an instrument adapted for precise measurements is required. It is possible, by means of Helmholtz's ophthalmometer, and more easily with Tscherning's ophthalmophakometer, to measure the curvature of the posterior surface of the cornea and of the two surfaces of the lens; but the knowledge of the refractive condition gained thereby is incommensurate with the difficulties to be overcome in the execution of these measurements.

The anterior surface of the cornea, however, can be measured so quickly and accurately that ophthalmometry—or, as it is more correctly called, *keratometry*—must be ranked among the valuable methods for the estimation of astigmatism. Since it reveals only the *corneal* astigmatism, this method is more limited in application than skiascopy. It must be borne in mind that while keratometry measures the curvature of the anterior corneal surface, it indicates not the *anterior* corneal, but the *total* corneal astigmatism (approximately), because the scale on the instrument is computed with the refractive index of the aqueous humor, not of the cornea (p. 128).

It is unnecessary to present a description of the mechanical appliances (which vary with the maker) of the modern keratometer, since anyone who wishes to make use of this instrument will more readily become familiar with it by practical experience. The essential parts for clinical use are: (1) A set of two objects whose images are to be examined, technically called (from the French) *mires*, centred on a common diameter

of the (2) telescope, and capable of being turned with the telescope into any corneal meridian, and (3) a device in the tube of the telescope for furnishing a double image of the mires as reflected from the cornea of the eye under examination.

The mires are white on a black ground. In the Javal-Schiötz instrument one of the mires is rectangular and the other is composed of a series of steps, each step being 5 mm. in breadth—an arrangement by which the degree of overlapping of the double image can be easily estimated. In recently constructed American instruments this form of mire has been discarded, being replaced by a form which is more suitable for rapid and accurate reading, while the degree of overlapping is read from a scale constructed for that purpose. The form of mire used in the Chambers-Inskeep keratometer is illustrated in Fig. 67.

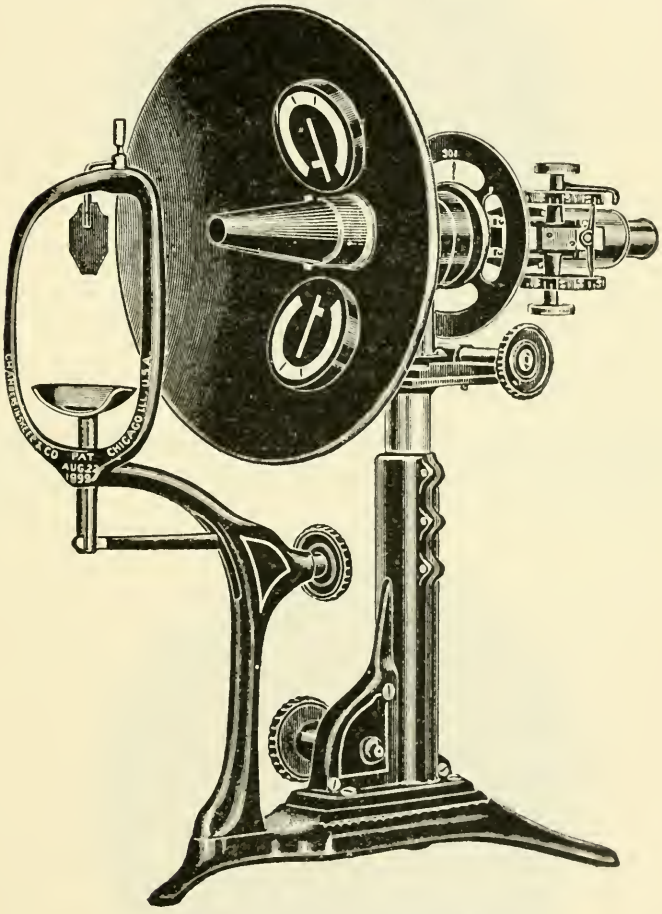
The large Placido's disk which forms the most conspicuous part of the 1889 model of the Javal-Schiötz instrument, is not required in the estimation of astigmatism; it is omitted in the American instruments, being replaced by a smaller plain black disk.

The first requisite in the use of the keratometer is suitable illumination. If sufficient daylight is available, the instrument is so placed that the mires receive light from a window; but ordinarily artificial light is preferable. This was formerly reflected from gas or electric lamps attached to the head-rest; but a great improvement has been made in the adoption of porcelain mires, which are transilluminated by small electric lamps.

As the mechanical appliances of the various models of the keratometer differ in many respects, it is impossible to give explicit directions for the use of this instrument. The outline here given is applicable for all models, but more particularly for the Chambers-Inskeep model, from which the illustrations are made. The patient

being properly seated before the instrument, the forehead and chin supported in the frame provided for that purpose, and the eye not under examination being covered by the blind attached to the head-rest, the

FIG. 67.

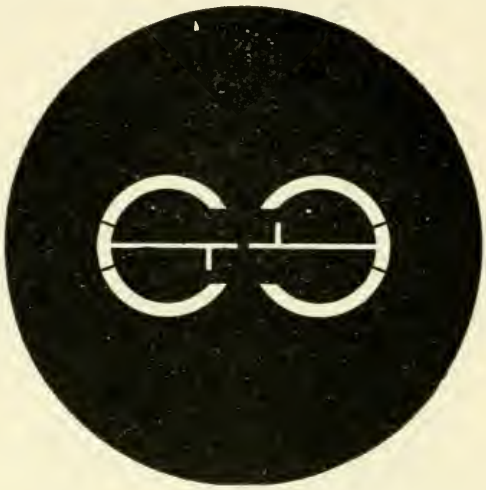


Chambers-Inskeep keratometer.

operator adjusts the tube of the telescope while the patient looks directly into the tube, taking care to keep the eye wide open, the two eyes on a level, and the forehead firmly resting in the frame. The operator then looking through the telescope sees the double

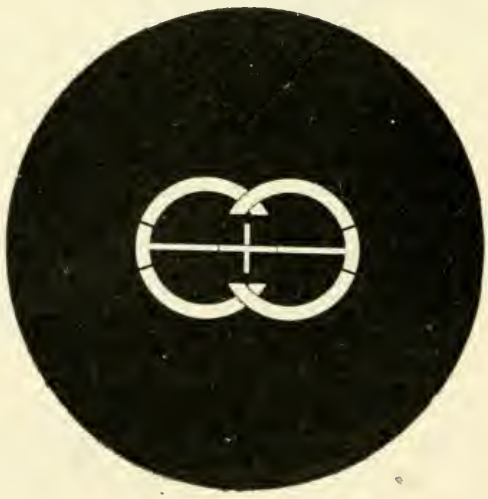
images of the mires reflected from the cornea; if these are blurred, they are brought into focus by proper

FIG. 68.



adjustment of the telescope. The instrument is then still further adjusted vertically or horizontally so as to

FIG. 69.



bring the two inner images into the centre of the field of view, the two lateral images being disregarded. After

this is attained the instrument is revolved until the long axial lines of the images show a single straight

FIG. 70.

and unbroken line (Fig. 68). If there is no corneal astigmatism this condition will exist in all meridians;

FIG. 71.

otherwise in only two meridians—the principal meridians of the cornea, or the *axes of the astigmatism*. An

axis having been thus ascertained, the *primary position* (Fig. 69) is obtained by adjustment of the mires (Javal-Schiötz), or of the double prism (Chambers-Inskeep), and the corneal refraction (in dioptres) is read from the scale and noted. The tube and mires are next rotated, and the slightest departure from the axial position is indicated in an astigmatic cornea by the appearance shown in Fig. 70. When the rotation has been carried through 90 degrees the axial lines of the mires are again continuous, as in Fig. 71. By proper adjustment the figure is again made to assume the form of a cross (similar to that in Fig. 69, but at right angles to it); this is the *secondary position*. The refraction of the cornea, as recorded on the scale, is again noted, and the difference between this and that marked in the first axis indicates the astigmatism in dioptres. In the Chambers-Inskeep model the refraction in the two principal meridians is recorded by two pointers, the interval between these representing the astigmatism.

In the Javal-Schiötz instrument the necessity of recording the refraction in each principal meridian is obviated by the stepped form of mire, an overlapping of each step in the secondary position representing 1 D. of astigmatism. But if the greatest curvature lies in the meridian first measured, there will be no overlapping, but an interval between mires in the second position; hence, to estimate the astigmatism in this case it is necessary to bring the images into the tangential position in this second position and then to revolve the instrument back into the first position, in which the overlapping now represents the astigmatism.

The outer (circular) portions of the mires (Chambers-Inskeep model) are useful in the detection of irregular astigmatism, in which the mires undergo irregular distortion. In regular astigmatism the circular portions appear more or less oval, according to the degree of astigmatism.

Since the cornea is not a mathematical surface, it sometimes happens that the meridians of greatest and least curvature are not strictly at right angles; the secondary position may be found to vary considerably from the rectangular axis. It should not, however, be thought necessary to place two cylindrical lenses in these obliquely inclined meridians, for we know that any two cylindrical lenses obliquely inclined are equivalent to a sphero-cylindrical lens, and, as far as such astigmatism is capable of correction—that is, as far as it is regular—the refractive error can be corrected by a cylindrical or sphero-cylindrical lens.

CHAPTER XII.

HYPEROPIA.

Hyperopia (H.) is that condition in which, when the ciliary muscle is in a state of relaxation, the retina intersects the axis of the optical system of the eye in front of the posteroir principal focus of this system, or it is that condition in which the antero-posterior diameter of the eyeball is too short in relation to the position of the posterior focus (p. 81).

Donders,[1] to whom we are very greatly indebted for our knowledge of this subject, introduced the term hypermetropia[2] to express this condition—a word which is the analogue of emmetropia; but because of its greater brevity, hyperopia (proposed by Helmholtz) is preferable—a term which corresponds also to the common expression *far-sightedness*.

The hyperopic state of refraction of itself reveals to us nothing as regards the curvatures of the surfaces, the indices of the media, or the size of the eyeball; it indicates only that there is a disproportion between these various factors, in which the eyeball is relatively too short. If the length of axis and the indices of the media approximate closely to the average which numerous investigations have established as the standard for the human eye, while the curvature of one or more of the surfaces is perceptibly less than the average, the result-

[1] Prior to the investigations of Donders hyperopia was confounded with presbyopia.

[2] From *ὑπέρ μέτρον*, beyond measure, and *ὤψ* sight.

ing hyperopia is assigned to deficiency of curvature and is called curvature-hyperopia. When the curvatures and the length of axis are normal, with a deviation from the average in one or more of the indices, any resulting hyperopia is called index-hyperopia; and when the curvatures and indices are normal, the hyperopia is attributable to deficiency in length of axis, and is called axial hyperopia.

Curvature-hyperopia.

Curvature-hyperopia is not common. Ophthalmometry shows us that ordinarily in hyperopia the curvature of the cornea and of the lens is not below the average, although exceptionally the radius of the cornea may so much exceed the standard as to produce hyperopia in an eye of normal length. An increase of intra-ocular pressure is capable of producing a flattening of the cornea, and in this way hyperopia sometimes develops or increases in glaucoma.

The hyperopia which exists in aphakia, since it is due to absence of the lenticular curvature, may be regarded as curvature-hyperopia.

Index-hyperopia.

The refractive index of the aqueous and vitreous has been found so nearly constant in health that we are justified only under exceptional circumstances in ascribing hyperopia to abnormal index of these media. The density of both media is sometimes increased from the presence of sugar, and the resulting increase in refractive index gives rise to hyperopia, since the power of the crystalline lens is thereby diminished, and to such

an extent as to outweigh the increase of convergence which takes place in the corneal refraction. In this way is explained the hyperopia that has occasionally developed in diabetes.

Index-hyperopia may also occur from the equalization of the refractive index throughout the lens, as usually takes place with increase of age. As the density of the outer layers of the lens approximates that of the nucleus, the refractive power is diminished and hyperopia may result.

Hyperopia due to the absence of the crystalline lens, which has been classed as a curvature defect, may, with equal propriety, be regarded as index-hyperopia, for in this condition the total index of the eye is abnormally low.

Axial Hyperopia.

Occasionally axial hyperopia occurs from pathological displacement of the retina, as in partial detachment; but ordinarily it is due to congenital deficiency in the antero-posterior diameter of the eye as compared with the average normal diameter. This is the typical form of hyperopia, and to it we assign practically all cases unless there is positive evidence that it is due to other cause. We must not forget, however, that in the lowest grades of hyperopia this is an arbitrary distinction, for an extremely slight variation in axial length—such as occurs in emmetropia—will effect a refractive change of several dioptres, unless accompanied by suitable adaptation of curvature or index.

The method of determining the deficiency in length of axis was demonstrated in Part I. (p. 89). In the manner there described the following table has been constructed, indicating the length of axis and the deficiency in various grades of hyperopia as measured by the correcting lens placed at the anterior focus of the eye:

Hyperopia.	*Length of axis.*	*Deficiency.*
0 D. (Emmetropia)	23.2 mm.	
1 D.	22.9 "	0.3[1] mm.
3 D.	22.2 "	1.0 "
5 D.	21.5 "	1.7 "
7 D	20.9 "	2.3 "
9 D.	20.2 "	3.0 "
11 D.	19.5 "	3.7 "
13 D.	18.9 "	4.3 "
15 D.	18.2 "	5.0 "

From this table it appears that a shortening of 1 mm. in the antero-posterior diameter of the eye corresponds to a hyperopia 3 D.; but this amount of shortening is by no means incompatible with emmetropia, and therefore there is no demonstrable deficiency in length of axis in the lower grades of hyperopia.

If emmetropia is regarded as the normal state of the human eye, the axially hyperopic eye must be regarded as an eye which has not attained perfect development. In this respect such eyes resemble those of the lower animals and of children, in whom hyperopia is the normal condition. A large number of examinations reveals an average of about 3 D. of hyperopia in newborn children. This, however, does not indicate an antero-posterior diameter of 22.2 mm., as it would in an adult; the average length of axis in the newborn is about 17 mm., the curvature of the cornea, and especially of the crystalline lens being proportionately greater than in the adult.

As age advances the eye increases in size, with a gradual diminution of hyperopia, which normally passes into a condition approximating emmetropia about the twelfth year. The proportion of eyes which reaches the emmetropic state varies with the communal habits, since

[1] Or, more accurately, 0.332 mm. It is apparent from the formula of derivation $\left(l' = \frac{FF'}{l}\right)$ that the deficiency in any degree of hyperopia, or the excess in any degree of myopia, as these defects are measured from the anterior focus of the eye, is derived by multiplying 0.332 mm. by the dioptric number of the correcting lens.

the eye in a measure adapts itself to the predominating requirements; the proportion may be approximately estimated as one-half in adults. In consequence of the irritation to which the eye is subjected during school-life, and in some cases because of inherent weakness of the sclera, the enlargement of the eyeball is frequently not arrested when emmetropia is attained, and this further increase in the antero-posterior diameter gives rise to myopia. It is fortunate, therefore, that this tendency is counteracted by the natural state of hyperopia.

In savage races, in whom the influences tending to cause axial elongation have not been brought into action, the normal condition, even in adult life, is that of hyperopia.

The eyes of congenitally deaf persons are also usually hyperopic, and not infrequently to a very high degree; the cause to which is due the arrest of development of the auditory apparatus affects also the eye.

Degree of Hyperopia.

Hyperopia varies in degree from a condition imperceptibly differing from emmetropia, on the one hand, to microphthalmos, on the other. In the former case, therefore, it is limited by the accuracy of our means of diagnosis. In the earlier days of ophthalmology eyes having less than 1 D. of hyperopia were regarded as emmetropic; but now it is customary to measure 0.25D., and with some even 0.12 D., of refractive error. In doing this, however, one must not forget that an eye which at 6 metres, or less, accepts (without detriment to vision) a convex lens not exceeding 0.12 D. or 0.25 D., is more nearly emmetropic (adapted for distant vision) without the lens than with it.

When the hyperopia reaches such a degree that the eye may be considered microphthalmic, the refractive

error becomes a secondary matter, since defects in development of the media and of the nervous elements preclude the possibility of useful vision, even though the ametropia should be corrected. Hyperopia exceeding 14 D. or 15 D. does not occur (excluding aphakia) in eyes which possess useful vision; in fact, an amount exceeding 8 D. or 10 D. is seldom encountered.

Low-grade Hyperopia.—Under this heading are included all cases which are less than 3 D. Eyes possessed of such a degree of hyperopia are in their anatomical structure and in their physiological workings not inferior to emmetropic eyes so long as there is sufficient accommodative power to overcome the refractive error without undue nervous strain. Such eyes may, therefore, be regarded as normal, except that in the process of growth there has occurred a disproportion between the curvatures and the length of axis. There is, however, no ground for the belief (commonly held by non-medical persons) that the visual acuity of far-sighted eyes surpasses that of the normal emmetropic eye. It is true that the savage or the hyperopic frontiersman, or the sailor, may be able to distinguish a distant object which is imperceptible to a town-dweller; but this is because the former has by cultivation and by familiarity learned to analyze images which escape the attention of the latter.

Medium Hyperopia.—This embraces those cases which are not less than 3 D. and not more than 5 D. In this class there is usually an appreciable deficiency in the axial length of the eye. This is rendered apparent by turning the eye strongly to the nasal or to the temporal side, when there will be revealed an abnormally great curvature at the equatorial region of the eyeball, the appearance thus differing from that presented by the emmetropic or (to a still greater degree) by the myopic eye.

It is not only the eyeball that presents this characteristic appearance. The conformation of the face and cranium also frequently exhibits a flattened aspect; the bridge of the nose, the forehead, and the orbital borders all lacking the relief that is present in more fully developed skulls. This lack of development of the bones of the face occurring with imperfect development of the eye is very noticeable in certain cases of asymmetry of the face, the eye on the side of inferior development being smaller than that on the other side. There are, however, many exceptions to this concurrence, for equal refraction in the two eyes is not uncommon in asymmetry of the face, and *vice versa*.

High-grade Hyperopia.—This embraces all cases which exceed 5 D. In such cases the smallness of the eye is not confined to the antero-posterior diameter: the eye is noticeably small in all its dimensions. The cornea also, as we should suspect, is abnormally small, and with this deficiency in size its curvature is not infrequently greater than that of the emmetropic eye.

The imperfect development in this grade of hyperopia often extends to the nervous mechanism—as characterized by pallor and irregularity of outline of the optic disk, or, at times, by increased redness, simulating neuritis. In such cases normal visual acuity is not to be expected after correction of the refractive error.

Latent and Manifest Hyperopia.

A part or the whole of the hyperopia of an eye may be overcome by involuntary tonic contraction of the ciliary muscle. Hyperopia so overcome is said to be *latent* (Hl.). Its existence can be ascertained only by ophthalmoscopic examination in a darkened room, or by paralysis of the ciliary muscle by means of a cycloplegic.

When the ciliary muscle relaxes to some extent so that a certain portion of the compensating accommodation may be replaced by a convex lens, the strength of this lens represents the *manifest* hyperopia (Hm.). The sum of the manifest and latent hyperopia constitutes the *total* hyperopia (Ht.).

The proportion of total hyperopia which remains latent varies in individuals and at different ages. From complete latency so often found in childhood, a gradually increasing portion becomes manifest with the weakening of accommodative power, so that in old age the total hyperopia is manifest.

Manifest hyperopia may be either *facultative* (Hf.) or *absolute* (Ha.). A hyperope of 3 D. may have normal distant vision without any correcting lens; if he still has normal vision with a convex lens not exceeding 1 D., he has 1 D. of manifest and 2 D. of latent hyperopia; and since he is able by exercise of accommodation to overcome the manifest hyperopia, the latter is said to be facultative. But when this same person is fifty-two or fifty-three years of age he has at his disposal only about 2 D. of accommodation. At this age the total hyperopia will be manifest, but only 2 D. of this manifest hyperopia can be overcome by accommodative action; hence he has 2 D. of facultative and 1 D. of absolute hyperopia.

Symptoms of Hyperopia.

The *subjective* symptoms of hyperopia vary with the degree of the defect, with the accommodative power, and with the occupation and nervous irritability of the individual. Hence, we must not be surprised to find a slight hyperopia causing very great annoyance in one person, while a much higher degree in another person may cause no disturbance whatever.

Vision in Hyperopia.—So long as there is sufficient accommodative power to overcome the error vision is unimpaired. Hence in slight hyperopia distant vision may be normal until an advanced age, and near vision may be affected only in that reading glasses are required at a slightly earlier age than in emmetropia; but when the hyperopia reaches the medium degree near vision becomes burdensome in early adult life, and distant vision also becomes subnormal before middle age. Thus a hyperope of 4 D., when he reaches the age of forty years, has only 4.5 D. of accommodation, leaving only 0.50 D. in reserve after adapting his eye for distant vision; hence he could not maintain normal distant vision for more than a brief period, and near work, such as reading ordinary print, would be clearly impossible.

In the highest grades of hyperopia it is apparent that vision must fall below normal at a still earlier age, and distant vision may be defective in childhood, even though there may be no arrest of development of the nervous mechanism.

Owing to insufficiency of accommodation in low and medium hyperopia there is a tendency for the person, as he grows older, to hold his book or other work at an abnormally great distance, by which means less accommodation is required, although retinal images are at the same time reduced in size. But, on the other hand, in the highest grades of hyperopia distinct images for near work are not possible even in childhood, and the child, learning this, abandons the attempt to secure distinctness, and instead obtains larger images by holding his work very near the eyes, thus leading the casual observer to the erroneous conclusion that the child is near-sighted.

Defective vision may also arise in hyperopia from abnormal weakness of the ciliary muscle, such as occurs in convalescence from exhausting diseases, or from paralysis of the third nerve, as in diphtheria.

Asthenopia.—This term is used to designate a group of symptoms characterized by pain in and about the eyes and in the frontal region, extending at times beyond the temples and even as far as the occiput and nape of the neck. These disturbances are produced by close application of the eyes, which tire easily; in a short time the print becomes blurred or unsteady, and pain, accompanied at times by photophobia, redness and watering of the eyes, becomes so great that cessation from work is imperative. After a period of rest the symptoms disappear, but upon resumption of work they recur with aggravated intensity. Asthenopia (eye-strain) sometimes gives rise to nausea, or to vertigo, and less commonly to insomnia, mental depression, nervous prostration (so called), and (according to some ophthalmologists) to chorea, epilepsy, and other reflex disturbances.

Asthenopia may result from any one of several causes: (1) *Hysterical, nervous,* or *retinal* asthenopia occurs in hysterical and neurasthenic persons as a manifestation of nerve-exhaustion, and it occurs not infrequently in eyes which are apparently normal. (2) *Muscular* asthenopia results from muscular imbalance, which necessitates an abnormal strain to preserve binocular vision. Since the normal relation between accommodation and convergence is disturbed in hyperopia, it might be inferred that muscular asthenopia would be one of the commonest symptoms in this affection; but, since hyperopia is congenital, the relation between convergence and accommodation is, as a rule, either modified to suit conditions (as in low hyperopia), or else binocular vision is abandoned at an early age, when the incentive to it is slight, and the unused eye passes into a state of strabismus—a common accompaniment of medium and high-grade hyperopia. (3) *Accommodative* asthenopia results from overuse of the ciliary muscle, and since this muscle has the greatest tax

thrown upon it in the hyperopic state of refraction, accommodative asthenopia is pre-eminently the asthenopia of hyperopic eyes.

Headache.—This has been mentioned as being one of the manifestations of asthenopia, but it sometimes occurs without any symptoms directly referable to the eyes. Ocular headache may consist in a dull pain in the forehead, supra-orbital neuralgia, occipital pain, usually combined with frontal headache, or severe migraine or sick headache. Pain at the vertex is sometimes, though rarely, attributable to eye-strain.

Objective Symptoms.—The characteristic form of the face and of the eyeball has been mentioned in the present chapter. In addition to these indications there are not infrequently found marginal blepharitis, conjunctival congestion or inflammation, or epiphora, and sometimes, from prolonged eye-strain, congestion and haziness of the retina in the region of the optic disk are observed upon ophthalmoscopic examination; but these symptoms are not pathognomonic. Such symptoms as may be so regarded have been fully considered under the head of objective methods of determining the refractive condition. (See Chapter XI.)

Strabismus in Hyperopia.—In hyperopia (except in the milder grades) distinct images are obtained in near vision only through very great effort of accommodation, and this excess of accommodation is accompanied by a correspondingly great innervation of convergence. If the desire for binocular vision predominates, the excess of convergence will be overcome, either by the acceptance of blurred images (with less accommodation) or by maintaining the muscular balance at the expense of undue nervous energy, giving rise, perhaps, to muscular asthenopia; but if the incentive to binocular vision is outweighed by the other factors, one eye will be used for vision while the other assumes a position of excessive convergence, thus constituting *internal* or

convergent strabismus. Hence, anything which weakens the natural impulse for binocular vision facilitates the occurrence of strabismus. Thus this defect frequently appears after loss or diminution of sight in one eye, or when one eye is congenitally defective, or if the refractive condition is unlike in the two eyes.

The strabismus which may be assigned to hyperopia as the chief causal factor usually occurs at an early age (in the second or third year), when the habit of binocular vision has not become strongly fixed and when the secondary image, falling upon a peripheral portion of the retina, seems to attract no attention. Sometimes the onset of the strabismus is delayed until the beginning of school-life, and its occurrence may be due to debilitating illness, as measles, scarlet fever, or diphtheria. In consequence of the weakness of accommodation following such diseases, a greater effort is required to secure the proper action of the ciliary muscle than in health, and with this effort excessive convergence may be unavoidable.

Convergent strabismus is most frequent in medium degrees of hyperopia. In the lower grades the relation between the two functions of accommodation and convergence usually becomes adapted to the altered conditions, provided there is normal incentive to binocular vision. In the highest degrees of hyperopia distinct images in near work are impossible, and the effort to secure them is not attempted. In such cases there may be binocular vision with indistinct images in both eyes, or binocular vision may be abandoned, the work being brought very near the eye for the sake of enlarged images. In the latter case, since there is no attempt to form distinct images with the aid of accommodation, there is no incentive to convergence, and the unused eye may fall into a state of divergence, thus producing the *divergent strabismus* which sometimes occurs in high degrees of hyperopia.

Diagnosis of Hyperopia.

Hyperopia may be suspected from the presence of some or all of the above-mentioned symptoms; but its existence is demonstrated and its degree estimated by means of the subjective and objective tests considered in Chapter XI. In the routine examination for the determination of refractive error the objective examination is usually conducted first (or after a short preliminary subjective examination), beginning with keratometry. Keratometry is useful in hyperopia only in so far as it reveals the coexistence of corneal astigmatism; yet by its aid we are enabled to observe the corneal curvature in every eye presented for examination, which is desirable as a matter of interest and comparison.

After completion of the keratometric examination skiascopy is next in order. The indications for the employment of a cycloplegic in this test are the same as in the subjective examination with trial lenses.

Owing to the greater accuracy of skiascopy, ophthalmoscopy is no longer used in the final estimation of refractive error. It possesses, however, one advantage over the former method in the examination of young persons without cycloplegia; if the direct method is used in a thoroughly darkened room, accommodation will usually be relaxed, whereas in skiascopy it is difficult to prevent a child from looking at the mirror or at the examiner. Ophthalmoscopy also enables the examiner to note the condition of the media and of the fundus, and to judge thereby whether or not normal vision will be afforded by correction of the refractive error.

In strabismus and in high hyperopia it is often necessary to correct the error before the child is old enough to submit to the subjective examination; in such cases reliance must be placed upon ophthalmoscopy and skiascopy with cycloplegia.

After completion of the objective examination, the subjective test with letters and trial lenses is undertaken. The manner of conducting this has already been described (p. 190). It remains only to state that the accommodation of all children suffering from eye-strain should be thoroughly paralyzed before attempting to estimate accurately the refractive error.[1] Atropin is the most suitable drug for this purpose, and the prolonged rest which it enforces is of itself beneficial. After the age of fifteen years (and before this in case of necessity) homatropin may be used and, if properly applied, will usually be found satisfactory. Between the ages of twenty and thirty years a cycloplegic should be used as a routine practice, being omitted only in exceptional cases, in which its use would cause great inconvenience, but never in cases in which correction of the manifest error alone has failed to give relief. After the age of thirty years cycloplegia is not, as a rule, required, yet even here it may be of material assistance in difficult cases.

Treatment of Hyperopia.

The degree of hyperopia having been ascertained, in accordance with the preceding directions, it remains to prescribe such lenses as will afford the eye, if possible, its normal or physiological working power. Ophthalmologists differ in opinion regarding the course to be pursued for the attainment of this end. Some maintain that latent hyperopia does not require correction, while others believe that the eye should in every case be placed in a condition of emmetropia by means of lenses correcting any deviation from this ideal condition. Neither of these plans should be

[1] When a cycloplegic is used the eyes should be protected from excess of light by smoked glasses until the mydriasis has disappeared.

blindly followed; it is impossible, indeed, that any general rule should be formulated, for each case must be judged in accordance with the symptoms and attendant circumstances. While the estimation of refractive error is in most cases a simple procedure, the prescribing of proper lenses is a far more difficult matter, and it requires much thought and care. All that may profitably be formulated is an outline of the method usually to be pursued, leaving to the judgment of the reader the modifications to be made in practical work.

Correction of Low-grade Hyperopia in Childhood.—It is almost incredible that hyperopia of 0.50 D. or 0.75 D. should be capable of causing asthenopia or other disturbance in a healthy child who has at his disposal 10 D. or 12 D. of accommodation. In those children in whom the correction of so slight an error brings relief, it is likely that the beneficial result is due to psychic influence, and not to the aid which the lenses give to the accommodation. That many children desire to wear glasses for egotistical reasons is unquestionable; yet since such influences are not unimportant in the production of subjective symptoms, it may perhaps occasionally be proper to prescribe weak lenses in a case of this kind, with the instruction that they are to be worn only for near work, and with the statement also, in the presence of the child, that a cure will be effected in a short time. In almost all these cases the symptoms will be relieved and the glasses discarded in the course of a few weeks or months.

On the other hand, it must be borne in mind that while hyperopia is the natural condition in childhood, the school-life of the child of modern civilization is artificial, and it may well be that the accommodation which is ample for a life in accordance with nature is insufficient, even in moderately low hyperopia (1.5 D. or 2 D.), to stand the strain of near work entailed by school duties. In such cases glasses should be or-

dered for school use and for reading. A portion only of the hyperopia should be corrected, because total correction would entail defective distant vision—a manifest disadvantage in school work. As a rule, not more than one-half or two-thirds of the total correction can be comfortably worn before the age of fifteen years; this limit may, however, be exceeded if the symptoms of the case indicate a necessity for such action.

Correction of Low-grade Hyperopia in Adult Life.—Low-grade hyperopia which has passed unnoticed in childhood requires correction sooner or later in the adult. The age at which this becomes necessary varies with the amount of error and with the health and occupation of the individual. As a rule, relief will be sought early by accountants, typewriters, and others engaged in exacting near work, and especially by women so employed, since their nervous organism is more delicate than that of men. If the hyperopia is latent, and especially if it is slight (not more than 1 D.), the use of glasses in near work will ordinarily suffice; on the other hand, manifest hyperopia indicates that the glasses should be worn constantly, although many who object to being so enslaved obtain relief from the use of working glasses. This is more especially the case with elderly persons who are not engaged in exacting work.

When correction of the manifest error, required for constant wear, is insufficient for near work, it may be necessary to order two pairs of glasses, the manifest correction for distance, and total correction for near work; but ordinarily a judicious selection of a single pair for all purposes will afford relief until the onset of presbyopia.

Correction of Medium and High-grade Hyperopia.—A medium grade of hyperopia may pass unnoticed throughout childhood; but usually, and especially in town life, it will give rise to asthenopia early in the

school career. In the correction of hyperopia reaching this degree (3 D.) glasses must be worn constantly, as a rule, even in childhood, for the proper relaxation of the ciliary muscle can be obtained only by prolonged training with the use of the correcting lenses; moreover, a fixed relation between accommodation and convergence cannot be established unless the glasses are worn constantly. The proportion of hyperopia to be corrected must vary with the age, as previously indicated, and with other circumstances, in accordance with which the examiner must judge as to the proper lenses to be prescribed.

Similarly high-grade hyperopia requires correction at an early age—at or before the beginning of the school career.

Treatment of Muscular Disturbances.—Muscular asthenopia or strabismus, in so far as either of these affections may be directly due to hyperopia, requires only the treatment appropriate for the causal refractive error; but the concurrence of muscular disturbance is a factor which must be considered in the prescription of correcting lenses. Even in mild hyperopia, in which during childhood correction for near work might otherwise suffice, it would be imperative that glasses should be worn constantly, if the hyperopia should be complicated by strabismus; furthermore, it would not be advisable, as previously recommended, to leave any considerable part of the latent hyperopia uncorrected. The total hyperopia should usually be corrected, even at the sacrifice of distinct distant vision, and relaxation of the accommodation should be aided, if necessary, by a prolonged course of atropinization, extending over a period of a month or more.

Whereas in uncomplicated hyperopia correction is not often called for before the school age, the occurrence of strabismus requires correction of the hyperopia at the earliest age compatible with the wearing of glasses—

usually between the second and third year, though by some children glasses will be tolerated before the end of the second year.

When a muscular disturbance which may have been originally produced by hyperopia has become so fixed through neglect that correction of the hyperopia does not restore the proper muscular balance, resort must then be had to other measures; these will be considered in Chapter XVII., dealing with muscular anomalies.

Secondary Effects of Convex Lenses.

In the application of lenses to the correction of hyperopia, there are certain secondary effects which not infrequently create confusion until the eyes become accustomed to the altered conditions.

Enlargement of the Retinal Image.—We have learned in Part I. (p. 87) that the retinal image in unaided axial hyperopia is slightly smaller than in emmetropia; and that the correcting lens exerts a magnifying effect upon this image, such that if the lens is placed at the anterior focus of the eye, the resulting image is of the same size as that of the emmetropic eye, and if the lens is farther from the eye than the anterior focus, the image is larger than that of the emmetropic eye. Since spectacle-lenses are usually of low power as compared with the refractive action of the eye, and since, although worn without the anterior focus, they are yet very near this point, the retinal image in corrected axial hyperopia does not materially differ from that in emmetropia. Hence, when a hyperope replaces his overstrained accommodation by convex lenses his retinal images are slightly larger than those to which he has been accustomed.

In the curvature-hyperopia of aphakia the correcting lens is placed within the anterior focus of the aphakic eye, and the effect of the lens is to reduce the size of images, yet they are materially larger than in emme-

tropia and, consequently, larger than they were before extraction of the crystalline lens.

Apparent Magnification of Objects.—Of greater import than the actual change in the retinal image is the apparent enlargement produced by convex lenses—an effect which is due entirely to mental influence. No knowledge as to the size of an object is revealed by the size of the retinal image alone; it is the size of this image taken in conjunction with the estimated distance of the object that enables us to form a correct judgment as to the dimensions of an object.

The estimation of distance is a complex mental act, based upon previous experience and association of muscular actions. In this act the degree of accommodation and convergence exercised, the movements of the eyes required to fix every part of the object, and the knowledge as to the actual size of the object are all important contributing factors.

Convex lenses, by diminishing the amount of accommodation required to see an object distinctly, lead one to suppose that the object is more remote than it actually is, and, consequently, make the object appear larger than it is as seen with the naked eye. On this account objects usually appear abnormally large to the hyperope when he begins to wear correcting lenses, even though the actual enlargement of the retinal image may be inappreciable.

Alteration in the Relation between Convergence and Accommodation.—In uncomplicated hyperopia a certain convergence is accompanied by a greater amount of accommodation than in emmetropia; hence, when correcting lenses are worn the associated nerve centres must be trained to modify this relation so that it will conform to the emmetropic standard. This is a common cause of disturbance when glasses are first worn. When, on the other hand, hyperopia is accompanied by excessive convergence, the restoration of the

normal relation between convergence and accommodation is one of the benefits bestowed by the correcting lenses.

Prismatic Action of Convex Lenses.—When the optical centre of a lens lies in the line of vision the object seen undergoes no lateral displacement; but when an object is viewed through an eccentric portion of a lens the object will appear displaced toward the thinnest part of the lens, just as toward the apex of a prism; that is, in the case of a convex lens the object will be displaced away from the centre of the lens. Hence, when convex lenses are so adjusted that their centres lie without the lines of vision of the two eyes, any object viewed will be displaced toward the nasal side, and consequently, in order that the image may fall upon the macula each eye must be rotated toward the nose to a greater degree than when the object is viewed without the lenses; in other words, the lenses require an increase of convergence, and the object seems nearer than it does with the unaided eye. On the other hand, if the centres of the lenses are within the lines of vision, the lenses are comparable to prisms having their bases toward the nose, and convergence is diminished by their use.

The prismatic action of weak lenses is slight, but in lenses of high power, and especially in those required in aphakia, the disturbance arising from this action is sometimes so great as seriously to interfere with the comfort of wearing such glasses. However well these may be adjusted, it is impossible to look through their centres at all times, and with every variation from this position a different prismatic effect is produced.

Prescription and Adjustment of Lenses.

The oculist determines the refracting power of the lenses which he desires his patient to wear; the adjustment and adaptation of these lenses in suitable frames may, as a rule, be left to the optician, who has greater

facilities for this work than the oculist can have.[1] The latter, however, must be thoroughly conversant with the various kinds of frames and lenses which can be supplied, in order that he may be able to assist his patient in procuring the most advantageous adjustment; he must also be able to judge as to the accuracy with which the optician has performed his work.

In an order or prescription for glasses the lens which is to be furnished for each eye is indicated by the letter R (right) or L (left), as R + 3 D. sph.; L+3.5 D. sph.; it must also be stated whether the glasses are for constant (distant) wear or for near use, and in order to avoid mistake the patient's name and the date must be written on the prescription. The character of frames may also be specified, if deemed advisable.

In filling the foregoing prescription the optician would decide whether to supply biconvex or periscopic lenses; he would also be free to use his own judgment as to the size of the eye (technically so called) to be selected. In supplying convex lenses of low and medium power the periscopic (meniscal) form is generally selected; but in the high-power lenses required in aphakic conditions this form entails so much additional weight that the biconvex form is more commonly used, unless the periscopic lens is specially called for by the oculist's prescription. Plano-curved lenses are not much used and would have to be specially ground for any prescription, but the optician usually keeps in stock a supply of menisci, or periscopic lenses. The periscopic convex lens, as commonly supplied, has a concave curvature of —1.25 D. (that is, the curvature of a plano-concave lens of 1.25 D.) on the side next the eye with a suitable convex curvature on the other side. This is the

[1] If the patient cannot personally visit a competent optician, it is necessary to make certain facial measurements to ensure proper fitting of glasses. Suitable blanks and directions for making these measurements will be furnished by the optician.

form which would be furnished by the optician in filling an order for periscopic lenses.

Since anyone who wears glasses soon becomes accustomed to rotating his head instead of his eyes in side vision, a more perfect periscopic effect than can be gained by the above means is not required, except in rare instances or for special purposes. In any such case a special lens might be ground in accordance with the deductions of Percival[1] or Ostwalt,[2] who have investigated the form of curvature best adapted to extensive field of vision in various grades of lenses.

The oculist may prescribe the size of lens which he desires to have furnished; he can do this by means of a series of numbers or letters by which the sizes commonly used are designated. No. 4 eye (34 x 25 mm.) is the smallest size and is used only for very young children, No. 2 (36 x 25 mm.) being more commonly suitable in childhood; No. 1 (37 x 28 mm.) may be used in adolescence and in small-faced adults, No. 0 (39 x 30 mm.) and No. 00 (40 x 32 mm.) being more commonly adapted for adults. Larger sizes, No. 000 (41 x 33 mm.) and No. 0000 (45 x 37 mm.), are sometimes used. These designations are required only when the patient cannot in person receive the attention of a competent optician, since the latter will be able himself to select the proper size of lens in conformity with the facial characteristics. It is only necessary to provide that inappropriately small lenses shall be avoided. Although only a small central portion is used for visual purposes, yet the lenses must be sufficiently large to prevent annoying reflections from their border. Very large lenses are not, however, required, and these should be avoided, since they are disfiguring.

Verification of Lenses.—Lenses having been prescribed by the oculist in accordance with the foregoing

[1] Percival, Arch. of Ophth., vol. xxx. p. 520.

[2] Ostwalt, Ibid., vol. xxxi. p. 35.

directions, it is his further duty to verify these lenses and their adjustment, and for this purpose he should instruct his patient to return to him after procuring the glasses from the optician.

The verification of the dioptric power is made in accordance with instructions previously given (p. 184). The method of finding the position of the optical centre has also been explained (p. 184). If the frames are properly adjusted, the glasses should be as near as possible to the eyes without touching the lashes, and the optical centre of each lens must lie in the line of vision, this being determined with the eyes in a state of parallelism or sight convergence and directed slightly downward if the glasses are intended for constant wear; but if they are for near work, the centres should be adjusted so as to be in the lines of vision with the eyes converging and directed downward, as at the ordinary reading distance. It is also advantageous in the adjustment of near glasses that they should be tilted slightly downward so as to obviate the necessity of looking obliquely through them. According to Duane, they should be dropped 5 or 6 mm., tipped forward 15 degrees, and the centre of each glass carried in toward the nose 3 mm.[1]

[1] Posey and Wright's Diseases of the Eye, Nose, Throat, and Ear.

CHAPTER XIII.

MYOPIA.

Myopia (M.) is, as previously defined (p. 81), that condition in which the retina lies behind the posterior principal focus of the eye when the ciliary muscle is relaxed; or it is that condition in which the eye is too long relatively to the principal focal distance.

The word myopia[1] originally indicated the practice of looking at objects through the partly closed lids, whereby the blurring of images is diminished; but as this habit is common in other conditions also, the expression is not, from a scientific point of view, altogether satisfactory. Donders proposed the word *brachymetropia*,[2] as corresponding with emmetropia and hypermetropia, but the old designation myopia continues in general use. The expressions *near-sightedness* and *short-sightedness* are also used in reference to this condition.

Curvature-myopia.

Ophthalmometric examinations by Helmholtz, Donders, Knapp, and others have failed to show any general excess of curvature, either of the cornea or lens, in myopia; on the other hand, their results indicate that the curvature is slightly less in the large eyes of myopia than in emmetropia and hyperopia. Exceptionally, however, myopia is due to excessive curvature,

[1] From *μύειν*, to shut, to blink, and *ὤψ*, sight, eye.
[2] From *βραχὺ-μέτρον*, short measure, and *ὤψ*, sight, eye.

as in keratoconus (conical cornea), lenticonus, and subluxation of the crystalline lens. In keratoconus the curvature of the cornea at its apex is so great as to give rise to very high myopia, which may attain to 45 D. or more. Lenticonus is a very rare condition; myopia from excessive curvature of the lens is more commonly the result of subluxation, the lens being relieved from traction of the ciliary ligament, but remaining in the pupillary area.

Index-myopia.

The only condition which, so far as we know, may give rise to index-myopia is an increase in the refractive index of the lens, such as sometimes occurs in old age and in the early stage of senile cataract. This increase of index may be due to an increase of density of the nucleus without a corresponding increase in the cortical part of the lens, or to an increase of nuclear curvature resulting from the swelling of the degenerating fibres. Since glasses which have previously been worn for the correction of presbyopia may no longer be required, the individual rejoices in the so-called *second sight*—at the expense, however, of distant vision, which becomes defective from the myopic state of refraction. This condition is usually temporary, being succeeded by declining vision as the result of opaqueness of the lens.

Axial Myopia.

Myopia is ordinarily due to excessive length of the antero-posterior diameter of the eye. That it might be due to this cause was suggested by Hermann Boerhaave (1746), a celebrated physician and professor in the University of Leyden. Morgagni demonstrated an increased length of axis in 1761; again, Beer, in 1817,

called attention to the fact that myopic eyes were frequently abnormally large and long; but it was through the demonstrations and publications of Arlt (1854) that the relation between axial elongation and myopia became generally understood.[1]

The following table, constructed in accordance with the method previously described (p. 223), indicates the theoretical length of axis in various grades of myopia, as measured by the correcting lens placed at the anterior focus of the eye:

Myopia.	*Length of axis.*	*Excess.*
0 D. (Emmetropia)	23.2 mm.	
1 D.	23 5 "	0.3 mm.
3 D.	24.2 "	1.0 "
5 D.	24.9 "	1.7 "
7 D.	25.5 "	2.3 "
9 D.	26.2 "	3.0 "
11 D.	26.9 "	3.7 "
13 D.	27 5 "	4.3 "
15 D.	28.2 "	5.0 "
17 D.	28.9 "	5.7 "
19 D.	29 5 "	6.3 "
21 D.	30.2 "	7.0 "
23 D.	30.9 "	7.7 "
25 D.	31.5 "	8.3 "
30 D.	33.2 "	10.0 "

It appears from this table that the axial length in myopia of 3 D. is 24.2 mm. If 1 mm. is allowed for the thickness of the chorioid and sclera, the antero-posterior diameter of the eye in this degree of myopia is 25.2 mm.; but an axial length of 25 mm. is not incompatible with emmetropia. Hence, in low degrees of myopia the size and shape of the eyeball differ imperceptibly, or at most but slightly, from the normal appearance; in high myopia, on the other hand, and especially in that exceeding 10 D., the elongation is so great as to effect a pronounced change in the form of the eye.

[1] Arlt, Die Krankheiten des Auges, Bd. iii.

As hyperopia is regarded as an imperfectly developed condition, so it might seem that the myopic eye has undergone excessive development. Since hyperopia is the normal type in the lower animals and in savages, there can be no doubt that the work to which the eyes are subjected by the requirements of civilization promotes an increased growth of these organs. Furthermore, it would be unreasonable to suppose that in this process, which occurs in conformity to the law of adaptation to use, a development which frequently stops short of emmetropia should never exceed this limit. It must be admitted, therefore, that low myopia *may* be due to physiological overgrowth of the eye. Yet in the vast majority of cases the excessive length arises, not from overgrowth, but from stretching or distention of the ocular coats. When the myopia does not exceed a moderate degree, the stretching is so slight that anatomical examination frequently affords no positive evidence of its existence; but the fact that the process is one of stretching and not of growth is revealed by the clinical progress of axial myopia, by the increase under the strain of near work, under unhygienic conditions, and by the arrest of the process when these factors are removed.

Theories as to the Origin of Axial Myopia.

While it is well established that the prolonged use of the eyes in near work is conducive to the formation of myopia, the means by which the enlargement of the eye is effected has given rise to much discussion. The various hypotheses which have been offered in explanation of the occurrence of axial elongation are divisible into two general classes: (1) Those which attribute the deleterious effect of near work to the prolonged exercise of accommodation, and (2) those which regard convergence as the causal factor.

Coccius and Hjort were led to believe from their experiments that the intra-ocular pressure was increased during accommodation (p. 153), and this supposition gave rise to the opinion, widely accepted, that distention of the sclera was due to the long continuance of this abnormal pressure. This hypothesis lacks confirmation, since it has never been proved that intra-ocular pressure is actually increased by accommodative action; on the other hand, experiments made by Hess and Heine indicate that accommodation does not cause any increase of pressure.[1]

According to another theory, accommodation is injurious, not so much from increase of pressure, as from the traction which is exerted upon the chorioid, thereby giving rise to chronic inflammatory changes with subsequent atrophy and thinning of the chorioid and sclera. This hypothesis has as its basis the experiments of Hensen and Voelckers, who demonstrated a forward movement of the chorioid during contraction of the ciliary muscle. There is, however, no valid reason for inferring that this physiological movement gives rise to inflammation; furthermore, the experiments of Hess and Heine show that it is only the anterior portion of the chorioid which participates in this movement, while the posterior portion alone is concerned in the development of myopia.

Those who hold accommodation responsible for the production of myopia, assign much importance to *spasm of the ciliary muscle.* But this is present in a large proportion of young persons who never become myopic, nor is it more common in myopic than in other eyes.

A potent argument against the accommodation theory lies in the fact that there is no general tendency to increase of refraction (diminution of the hyperopia) in

[1] Hess and Heine, Archiv für Ophth., xlvi., 2, p. 243.

those eyes upon which the greatest accommodative tax is thrown, that is, in the higher grades of hyperopia.

The influence of convergence upon the form of the eyeball is doubtless of greater import than that of accommodation. When the internal recti are strongly contracted, the external recti bind closely about the outer halves of the eyeballs, and at the same time the two oblique muscles must increase their traction in order to prevent the globes from sinking backward into the orbits. The pressure upon the eyes is thereby increased, *and a direct traction (stretching) is made upon the posterior polar region of the sclera by the oblique muscles.*

Arlt advanced the theory that convergence was harmful also from compression of the posterior ciliary vessels by the external recti and inferior oblique muscles, thus giving rise to venous stasis and consequent inflammation. Fuchs also claims, in corroboration of this theory, that the position of one of the venæ vorticosæ is such that it must suffer compression by the inferior obliques in convergence.

The influences which have been so far considered are such as are common to all who are engaged in exacting near work (eye workers); but since only a certain proportion (about 25 per cent. in this country and about 50 per cent. in Germany) of eye workers become myopic, it is necessary to assume the existence of *predisposing causes* in those eyes which become subject to elongation.

First, there arises the question as to the *influence of the form of the skull* upon the length of the eye. The largeness of the eyes and the great interpupillary distance which exists in highly-developed crania, render convergence more difficult of accomplishment than in small eyes and in those having a less interpupillary distance; hence, the large, broad type of skull is considered as a predisposing element in the formation of myopia.

Insufficient length of the optic nerve has also been assigned as a possible cause of myopia (Weiss). Those who have advocated this hypothesis believe that in certain cases the length of the optic nerve is not great enough to permit free movement of the eyeballs, as for the easy performance of convergence; but this assumption is apparently irreconcilable with the well-known fact that a much greater degree of adduction is always possible than can be manifested in convergence.

The small or negative angle gamma which, as shown by Donders, is common in myopia, has also been regarded as a factor in the production of this condition, since a greater convergence of the optic axes is required in such eyes than when the angle gamma is large.

In addition to these theoretical factors, there is to be considered the concurrence (as supported by abundant clinical evidence) of *visual defects* in myopia. Astigmatism, opacities of the media, imperfect development or atrophy of the retina, or other defect which reduces the visual acuity may act as a predisposing cause of myopia, since such defects render it necessary that objects must be held abnormally near the eyes in order to increase the size of the images as an offset to their indistinctness.

On the other hand, the relation between the visual defect and the myopia may not be causal; both may be manifestations of imperfect development of the eye. This is, doubtless, the most potent predisposing element in the etiology of myopia, namely, *subnormal resisting power of the sclera* at the posterior pole of the eye.

Posterior Staphyloma.

So great is the elongation in the highest grades of myopia that the sclera is reduced to paper-like thinness, and owing to the presence of the underlying chorioid the sclera assumes a bluish tint. From this fact the

condition, first described by Scarpa in 1807, received its name. Scarpa did not, however, connect this anomaly with axial myopia. The demonstration of this relationship was made by Arlt, but he erroneously regarded every axially myopic eye as affected with staphyloma—a term which is correctly applied only when there is demonstrable thinning of the sclera and atrophy of the chorioid at the posterior pole of the eye.

The Conus.—This is a whitish crescent (myopic crescent[1]) which is frequently found at the border (usually at the temporal border) of the papilla (Fig. 72). According to the statistics of Loring, this crescent is present in 20.5 per cent. of myopic eyes, in 3.33 per cent. of emmetropes, and in 3.49 per cent. of hyperopes.[2] From these statistics the conclusion is reached that the conus bears an important relation to the origin of myopia, but that its presence does not necessarily indicate tendency to this affection.

The so-called *annular* or *ring conus* is due to an abnormally large opening in the sclera at the entrance of the optic nerve (Fig. 73).

There are two opinions as to the nature of the conus: (1) That it is a circumscribed atrophy of the chorioid, due to stretching of this membrane in axial elongation, and (2) that it is a congenital peculiarity of development.

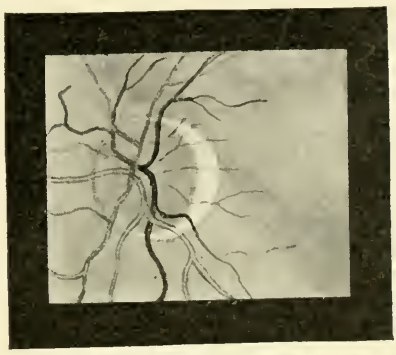
The former hypothesis is discredited by the regularity of outline of the conus, by its occurrence in emmetropic and hyperopic eyes, and by anatomical examinations, which have shown that in emmetropia and hyperopia and also in mild myopia the sclera and chorioid are perfectly normal beyond the limits of the conus.

[1] The conus (Jaeger) originally denoted the irregularly cone-shaped patch of atrophy extending from the crescent in staphyloma, but this term is now commonly used in reference to the crescent or to the exaggerated scleral ring.

[2] Trans. of the Internat. Med. Cong., Phila., 1876.

The second hypothesis—that the conus is due to congenital anomaly of development (absence of the anterior

FIG. 72.



The crescentic conus.

layers of the chorioid, pigment, and retina)—has been strenuously urged by Schnabel, who claims that his opinion is confirmed by microscopic examination.[1]

FIG. 73.

The annular conus.

Since it is a matter of clinical observation that a conus sometimes appears in an eye which has previously

[1] Relationship of Staphyloma Posticum to Myopia, Norris and Oliver's System of Diseases of the Eye, vol. iii. p. 395.

seemed free from this anomaly, Schnabel assumes that the conus was previously present, but that, being very small, it was not noticeable until, with an increase in the size of the eye, there occurred a corresponding increase in the size of the conus.

Two Theories as to the Origin of Posterior Staphyloma.—In accordance with these two theories as to the nature of the conus, there are two corresponding theories as to the origin of posterior staphyloma. Those who believe that the conus is ascribable to atrophy of the chorioid, believe also that the strain of near work may give rise to posterior staphyloma in an eye of perfectly normal development. On the other hand, those who see in the conus evidence of anomalous development, believe also that in addition to this defect there is in all staphylomatous eyes deficient development of the sclera at the posterior polar region.

While the conus is found in only about 20 per cent. of myopic eyes, it exists in practically all in which there is staphyloma; hence, if we accept this theory, the presence of the conus must be regarded as evidence, but not positive evidence, of congenital deficiency in resisting power of the sclera.

Whether we do or do not accept Schnabel's views as to the nature of the conus, clinical evidence is largely in favor of the theory that staphyloma occurs only in eyes of congenitally defective development. None of the influences which have been detailed as giving rise to myopia suffices to explain the occurrence of staphyloma in an eye of normal development. In such an eye the thickest and most resistant portion of the sclera is in the region of the optic nerve and posterior pole, and any increase of intra-ocular pressure which might result from near work would not be limited in its manifestation to this, normally, most resistant part of the eyeball. This is exemplified in glaucoma in young subjects, in whom distention of the sclera is general,

but is more marked in the region anterior to the insertions of the recti muscles (where the sclera is thinnest) than it is posteriorly; a *circumscribed posterior ectasia does not occur.*

The theory of traction by the optic nerve is equally incapable of accounting for the ectasia at the posterior pole, for the maximum effect of such traction would occur in the neighborhood of the disk, not at the pole.

In order to explain by this or other theory the occurrence of the circumscribed polar ectasia, we must assume the coexistence either of chorioidal inflammation extending to the sclera or of defective development. Against the former assumption are the clinical facts that chorioiditis does not in general extend to the sclera, and that chorioidal complications occur, not before, but after the scleral ectasia.[1]

But the most potent reason for believing that the insufficient resisting power of the sclera is congenital lies in the fact that the scleral ectasia almost always commences at an early age, before the eyes have been subjected to the injurious influences of near work. The eyes of newborn children are, as a rule, hyperopic; but it is beyond dispute that high myopia with staphyloma occurs at an early age. Among other cases which have been reported may be cited the following: myopia of 11 D. at the age of eighteen months (Eales[2]), 10 D. at the age of six months (Cant[3]), 17 D. at the age of four years (Wray[4]). These are extreme cases, but the occurrence of myopia varying from 4 D. to 8 D. in children under six years of age is by no means rare among the poorly-developed lower classes. These are

[1] We exclude here the congestion which frequently occurs at the border of the disk as the result of eye-strain in any kind of refractive error, and which is nowise indicative of staphyloma.

[2] Eales, British Med. Journal, 1890, vol. ii p. 727.

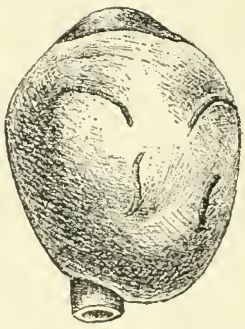
[3] Cant, Ibid., p. 727.

[4] Wray, Ibid., p. 728.

the cases which, unless checked by suitable treatment, always terminate in staphyloma with high myopia.

Anatomical and Ophthalmoscopic Characteristics.—The thinning of the sclera in posterior staphyloma is confined mainly to the segment which extends medially slightly beyond the edge of the optic nerve, and laterally to the attachment of the inferior oblique muscle. The region of the posterior pole or of the macula consequently lies near the centre of the staphylomatous area, and the greatest protrusion must occur in this position. This is illustrated in Fig. 74, in

FIG. 74.

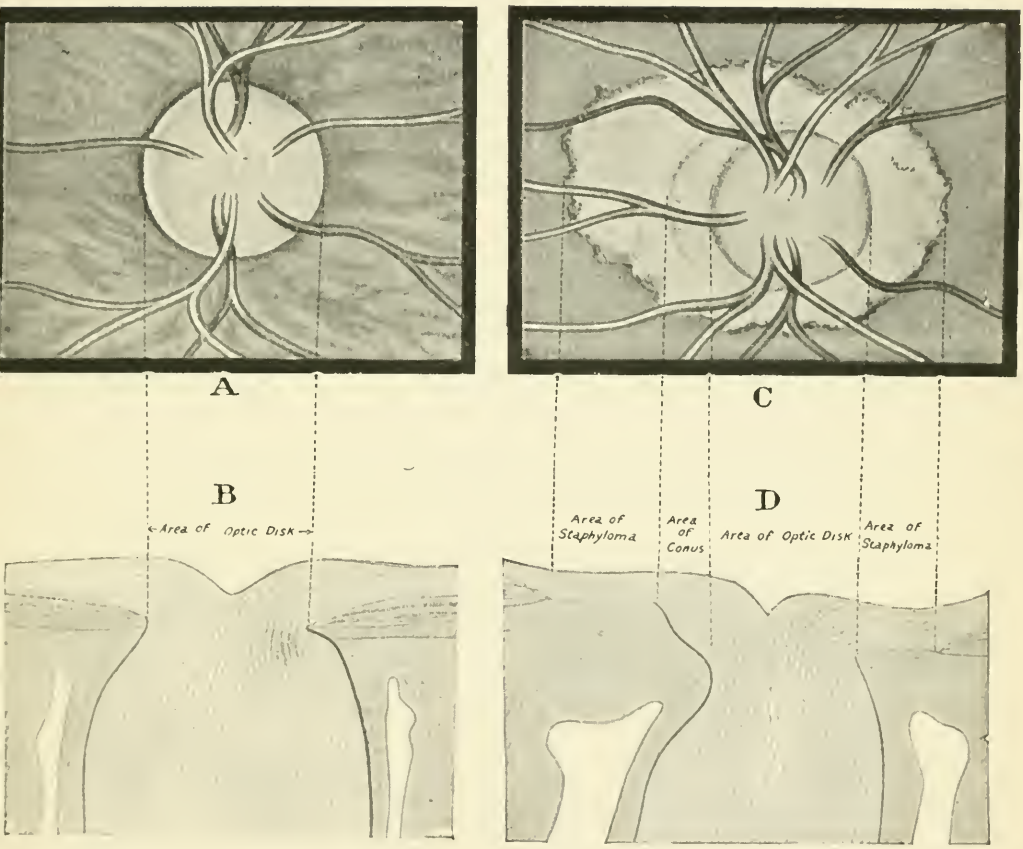


The right eye of a woman fifty-six years of age, with a large posterior staphyloma; myopia, about 25 D.; length of axis, 30 millimetres. (Schnabel, in Norris and Oliver's System of Diseases of the Eye.)

which the optic nerve lies on the side of the protrusion; but sometimes the ectasia extends more medially, and then the optic nerve lies, not as illustrated, but at the bottom of the protrusion.

In connection with the oblique position of the papilla there occur also peculiar changes in the appearance of the optic nerve in its passage through the sclera and chorioid. Opposite to the crescent the chorioid and retina seem to be drawn over the medial border of the nerve, as if the whole posterior portion of these membranes had shifted their position—supertraction of the chorioid (Nagel and Weiss). Furthermore, the entire head of

PLATE II.



NORMAL OPTIC NERVE ENTRANCE.

A. Ophthalmoscopic view.
B. Diagrammatic section.

POSTERIOR STAPHYLOMA.

C. Ophthalmoscopic view.
D. Diagrammatic section.

The Optic Nerve Entrance in its Relation to the Chorioid.

(Würdemann, in Posey and Wright's Diseases of the Eye, Nose, Throat, and Ear.)

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PLATE III.

Posterior Staphyloma with Large Patches of Secondary Chorioidal Atrophy.

the optic nerve is distorted, as if drawn over by distention of the sclera toward the staphyloma. This distortion is accompanied also by an abnormal size of the intervaginal space, as if the nerve had been drawn away from its normal attachment with consequent separation of the nerve sheaths. (Plate II.)

Ophthalmoscopically the oblique position of the papilla is a marked characteristic in staphyloma; it gives the disk an apparently oval form, which is accentuated when the retina extends over the medial border of the nerve.

The stretching of the chorioid and retina in staphyloma is first manifested by an increase in size of the crescent, and subsequently by atrophic changes in these membranes. The process commences at the outer border of the crescent, whereby the latter loses its regular contour and becomes merged in the larger, irregularly shaped, whitish patch. (Plates II. and III.) The atrophic area continues to increase in size and sometimes surrounds the entire disk, as in Plate II. (annular staphyloma). Other atrophic patches appear, in the worst cases, at or near the macular region (Plate III.[1]), and these are very disastrous to vision. Moreover, there is interference with the nutrition of the eye, so that other grave dangers threaten destruction of the small amount of vision which remains. Where the atrophic areas are surrounded by accumulations of pigment, the changes are not recent. An ill-defined yellowish patch signifies that the atrophy is still progressing. Not infrequently the atrophy progresses by intermittent stages, which are distinguished by separating lines, more or less defined, and marked at times by accumulation of pigment.

[1] This plate represents approximately (the drawing having been made from memory) the condition found in the right eye of a Polish woman, about forty years of age; myopia, 18 D.; central vision lost. In the left eye there was myopia of 13 D. with useful vision.

Two Types of Axial Myopia.

In accordance with the foregoing facts, we conclude that there are two types of axial myopia. The first embraces those cases which result mainly from the strain of near work during school-life, or from other exacting eye work. The refraction is, in this type, hyperopic in early childhood, and would probably remain so—or at least not pass the limit of emmetropia—during life if near work were excluded; but the irritation induced by the educational process leads to an increase in size of the eye, and myopia results. This most often occurs between the ages of ten and twenty years. The progress of the myopia may be arrested in childhood or it may continue until the body has attained its full growth; after this the sclera is more resistant, and the myopia remains stationary. It rarely, if ever, reaches a high degree; we may assign 6 D. as the limit, beyond which it does not often pass.

In myopia of this type the sclera does not undergo any appreciable thinning, and neither ophthalmoscopic nor anatomical examination reveals any defect except the conus, which may or may not be present.

Although distant vision without glasses may be very defective, yet because this type of myopia does not induce atrophic and other pathological changes, all such cases are classified as belonging to the *mild* type of myopia. Since such myopia is acquired during school-life, it has also been called *acquired* or *school* myopia.

The second type of axial myopia includes those cases which are dependent upon posterior polar ectasia. Every case of axial myopia which exceeds 10 D. may be assigned to this class (Schnabel), but even a moderate myopia (3 D. or 4 D.) occurring at an early age must be regarded as indicative of defective scleral development, which may subsequently give rise to staphyloma with great increase of the myopia.

Since in this class the myopia tends to increase, even after adult life is reached, and since even when the myopia itself has become stationary, atrophy, hemorrhage, opacities, and retinal detachment still threaten the eye, the name *progressive* or *malignant* myopia is appropriate.

Of those cases of axial myopia which are more than 6 D. and less than 10 D., a minority may be exaggerated types of acquired myopia; but for the most part they must be regarded as favorable cases of staphyloma. In fact, it is probable that in all such cases a deficiency in the development of the sclera has existed, and that at least in the greater proportion the elongation commenced prior to the age of near work; for it is certainly seldom that an eye has been observed to pass from hyperopia or emmetropia to a myopia exceeding 6 D. In those cases which do not become decidedly staphylomatous, the strength of the sclera is not greatly reduced, so that the elongation is arrested before the development of very high myopia.

Statistics of Myopia.

Many statistics have been published in regard to myopia. In those in which a large number of eyes was examined, the results are fairly uniform. These statistics relate mainly to the proportion of myopes at different ages, in different races, and in different occupations.

Of statistics which refer to *the proportion of myopes at different ages and in different races* Loring attaches especial importance to the results of four observers: Erismann, of St. Petersburg;[1] Conrad, of Königsberg,[2]

[1] Erismann, Arch. für Ophth., 1871, xvii., 1, p. 1.

[2] Conrad, Die Ref. von 3036 Augen von Schulkindern, Leipzig, 1875.

and Derby and himself, of New York.[1] A large number of eyes was examined by each of these observers, and the conditions were similar in all cases. The examinations were all made on school-pupils between the ages of six and twenty-one years.

According to Erismann's statistics (4358 pupils), 10 per cent. were myopic in the lowest classes, the proportion increasing to 42 per cent. in the highest; Conrad's statistics (3036 pupils) showed 11 per cent. of myopia in the lowest classes and 62 per cent. in the highest; Derby and Loring's (2265 pupils) showed 3.5 per cent. in the lowest and about 27 per cent. in the highest classes.

Many others have published statistics bearing on this subject, but those here given are sufficient to convince us that myopia is very frequently acquired during school-life, and that Americans are much less subject to this affection than Europeans.

Loring found in his examinations an especially small percentage among the Irish. English statistics also indicate a much smaller proportion of myopes than is found among continental Europeans.

Statistics have also been published showing *the change in refraction in the same individuals with increase of age.* Among these may be mentioned those of Erismann[2] (350 eyes re-examined after the lapse of six years), of Reich[3] (85 pupils, after six years), and of Cohn[4] (138 pupils, after one and one-half years). These statistics all show that there is a general tendency to increase of refraction (diminution of hyperopia or increase of myopia) prior to adult life, and that this tendency is most marked in the case of those who are already myopic; but in no case do they show that an

[1] Loring, Internat. Med. Congress, Phila., 1876.
[2] Erismann, Handbuch der Hygiene, Pettenkofer u. Ziemssen, ii., 2, p. 30.
[3] Reich, Arch. für Ophth., xxix., 2, p. 303.
[4] Cohn, Hygiene of the Eyes (English ed.), 1886.

eye previously recorded as hyperopic or emmetropic has attained a myopia exceeding 6 D.

Of the statistics relating to the *degree of myopia* among a large number of myopes, those of Schweizer[1] must be mentioned as being particularly useful. Among 5039 myopic eyes the myopia did not exceed 6 D. in 4029 of these; in 475 it was between 7 D. and 10 D., and in 535 it was more than 10 D.

Tscherning[2] has published very instructive data showing *the proportion and grade of myopia among different classes* of persons. He found that of 2336 eye-workers, 18 per cent. were myopic; of 5187 laborers, 4 per cent. were myopic. But of the myopic eye-workers, only 3 per cent. had myopia exceeding 9 D., while of the myopic laborers 18 per cent. had myopia exceeding 9 D. These figures indicate very clearly that while near work has a decided influence in the etiology of mild and moderate degrees of myopia, it is not a predominant factor in the production of posterior staphyloma.[3]

Statistics have also been published with a view to showing, by comparison with the older statistics, *the beneficial effect which hygienic care of the eyes of the young has exerted upon the proportion of myopes.* Risley[4] especially has made extensive investigations of this subject; his data, as well as those of others, indicate that a perceptible improvement follows the introduction of school hygiene.

Lastly, statistics have been published setting forth

[1] Schweizer, Archiv für Augenheilkunde, Bd. xxi. p. 399.

[2] Tscherning, Archiv für Ophth., xxix., 1, p. 252.

[3] This does not mean that near work exerts less injurious influence in staphyloma than in mild myopia, but that in the former the sclera has so little resisting power that it becomes distended without the intervention of eye-strain. In staphyloma avoidance of excessive use of the eyes is of the utmost importance.

[4] Risley, School Hygiene, Norris and Oliver's System of Diseases of the Eye, vol. ii. p. 376.

the influence of heredity in the etiology of myopia. These show that as some races are more liable than others to myopia, so also the members of certain families possess in a special degree the characteristics which lead to the formation of myopia.

Symptoms of Myopia.

Myopia of every grade is characterized by one predominant symptom: the inability to see distant objects clearly. Even in myopia of 0.5 D., in which the far-point is 2 metres from the eye, vision at 6 metres or more is perceptibly below the normal; but the power of analyzing objects varies according to the intelligence of the individual, the familiarity with the object under examination, and the size of the pupil of the eye.

The symptoms of eye-strain (asthenopia and congestion of the retina) which were described as occurring in hyperopia occur also in myopia. These symptoms are regarded by some ophthalmologists as indicating that the ocular membranes are undergoing a process of stretching. Whether or not this is the case, such symptoms cannot be said to play an important part in the etiology of staphyloma, since they frequently occur in eyes in which the elongation never passes the limit of emmetropia.

Muscular asthenopia, due to disturbance in the relation between accommodation and convergence, is a not uncommon symptom in myopia. Owing to the weak accommodative impulse required, the convergence-centre is insufficiently stimulated, thus giving rise to insufficiency of convergence (exophoria).

Insufficiency of convergence occurring in myopia may be due, not only to disturbed relation between

accommodation and convergence, but also to some anatomical peculiarity requiring unusual effort to produce convergence, such as abnormally great interpupillary distance, elongated eyeball, or unfavorable insertions of the internal recti muscles.

Divergent Strabismus in Myopia.—When the myopia exceeds 4 D., the far-point being within $\frac{1}{4}$ metre from the eye, binocular near work is almost always burdensome, since convergence at this distance is not easily prolonged. On this account myopes of this class generally abandon binocular vision (if they do not wear correcting lenses), using only one eye in near work, while the other turns relatively outward to a greater or less degree. The parallel direction may be maintained in distant vision; but frequently binocular distant vision is abandoned, and the unused eye becomes permanently divergent, the latent insufficiency passing into manifest strabismus. Hence, *divergent strabismus* is a not infrequent symptom of myopia, and especially of that exceeding 4 D.

Symptoms Arising from Disturbed Nutrition in Staphyloma.—In the high grades of myopia the far-point lies only a few centimetres from the eye, and, consequently, reading matter or small objects to be deciphered must be held just beyond the tip of the nose; but this is by no means the gravest symptom of high myopia. Those symptoms which arise from defective nutrition of the eye are such as to give to the myopia a position of secondary importance. Floating opacities in the vitreous body, high astigmatism from partial dislocation of the lens, polyopia from commencing cataractous degeneration, fixed scotomata from retinal atrophy or hemorrhage, metamorphopsia from serous effusion beneath the retina, and total blindness from retinal detachment are among the symptoms that are liable to occur in myopia with posterior staphyloma.

Diagnosis of Myopia.

Externally there is nothing markedly characteristic of mild myopia; but the elongation in staphylomatous eyes is apparent in the facial expression. These eyes are usually prominent and their large size is especially noticeable when they are turned sharply to one side. In addition, there is generally found an abnormal depth of the anterior chamber in the highest grades of myopia; but these appearances are mere incidentals, since the myopia and its degree may be readily determined by application of the tests which were enunciated in Chapter XI.

The order of applying these tests which was suggested for the estimation of hyperopia may be followed also in myopia, namely, keratometry (for the estimation of coexisting corneal astigmatism), skiascopy, ophthalmoscopy, and the subjective examination with trial lenses.

The rule which was advised for the employment of a cycloplegic in hyperopia is applicable also in myopia. While perhaps in a greater proportion of cases the true refractive condition may be ascertained without cycloplegia in myopia than in hyperopia, yet there is no certainty as to the correctness of the result in young persons unless the accommodation has been paralyzed. Hence, a cycloplegic should be used in all cases under twenty years of age, and, as far as practicable, in all under thirty years. It may be of assistance also in difficult cases beyond this age, though less frequently so than in hyperopia.

The ophthalmoscopic examination assumes a relatively greater importance in myopia than in hyperopia, since by it we are informed as to the condition of the interior of the eye—whether the myopic crescent, chorioidal atrophy, macular disease, opacity of the vitreous body, or other accompaniment of staphyloma is present.

Differentiation of Mild and Malignant Myopia.—There are three points to be especially considered in making the distinction between these two kinds of axial myopia:

1. *The Age at which the Myopia Develops.* Myopia occurring before the age of near work always indicates defective scleral development, which, unless promptly arrested, will probably terminate in staphyloma; on the other hand, myopia which is evolved from a condition of hyperopia during school-life, is indicative of the mild form and will not lead to destructive processes in the eye.[1]

2. *The Degree of Myopia.* Myopia which is less than 6 D. in an adult may be regarded as having been acquired during school-life and, therefore, as belonging to the mild form; or, exceptionally, it may denote an infantile myopia in which the progress of ectasia has been arrested, and in which further advance is not to be expected. Myopia which is between 6 D. and 10 D. must be regarded as probably due, in adults, to arrested ectasia; in youth an advancing process must be assumed. Myopia exceeding 10 D. always indicates staphyloma.

3. *The Ophthalmoscopic Appearances.* The presence of the conus is evidence of staphyloma only in that while frequently absent in mild myopia it is always found in staphyloma. Positive proof of staphyloma is afforded by the existence of chorioidal atrophy extending beyond the border of the crescent with or without atrophy in the macular region.

Diagnosis of Curvature-myopia and Index-myopia.—In the small minority of cases in which high myopia is due to conical cornea, the characteristics are altogether different from those in axial myopia. The

[1] Some oculists, as previously stated, do not agree to this, believing that staphyloma may develop (as the result of strain) from a condition of hyperopia.

symptoms of posterior staphyloma are absent, while the excessive curvature of the central portion of the cornea is revealed by keratometry, by skiascopy, and by the unaided eye in advanced cases.

The myopia which occurs in old age from swelling or increase of density of the nucleus of the lens is also readily differentiated from axial myopia by the period of life at which it develops, by the abnormally intense nuclear reflex, and by the detection of lenticular opacities.

Treatment of Myopia.

Since it is well established that prolonged near work tends to favor the myopic state of refraction, and since it would be a grave misfortune if, with the advance of civilization, myopia should become the ordinary condition of the human eye, we must do all that is in our power to combat this tendency by hygienic and artificial means. Whatever acts favorably in the individual exerts also a beneficial influence upon the resisting power of the eyes of future generations.

Prophylactic Measures.—In the first place, young children should not be permitted to indulge in exacting near work, since it is at this period that the sclera is most distensible. They should not commence school before the completion of the seventh year of age; and at the beginning of school-life and at least once a year thereafter the vision should be tested in order that those in whom it is found defective may receive appropriate treatment.

The correction of astigmatism is especially important, since the defect of vision caused by it necessitates an abnormal approximation of objects, with excessive strain on the accommodation and convergence.

When the vision is markedly defective and is incapable of improvement, the child should not be per-

mitted to pursue the full course of study required of healthy children.

Since anything that interferes with the bodily nutrition must exert an unfavorable influence upon the strength of the sclera, and since posterior staphyloma is most liable to occur in children of defective constitution, it is essential that school hours should be broken by suitable out-of-door exercise, and that other matters of general hygiene should receive proper attention.

Of no less importance are the arrangements of the school-rooms as to light and ventilation, and the adaptation of the desk to the pupil (for the avoidance of the stooping posture with the consequent congestion of the head and eyes), and the quality of the paper and print used in the text-books. Much thought has been given this subject of school hygiene of late years, and great improvements have been effected.[1]

The attention given these matters should extend also to office rooms and factories, in which the eyes of the employés are taxed to the utmost during a period of eight or ten hours each day. In those occupations which necessitate the prolonged examination of small objects, a magnifying glass, such as is used by watchmakers, should be employed as far as possible. By this means both accommodation and convergence are relieved of the strain to which they would otherwise be exposed.

Use of Lenses in Myopia.—While all authorities are agreed as to the beneficial effect of hygienic measures, the influence of correcting lenses upon existing myopia is a question about which there has been some difference of opinion. Those who believe the myopia to be the result of overexercise of accommodation con-

[1] For fuller discussion, consult Risley, School Hygiene, in Norris and Oliver's System of Diseases of the Eye, vol. ii. p. 353.

demn the use of concave lenses in near work. Those, on the other hand (including the large majority of oculists of the present day), who believe that convergence, not accommodation, is the main factor in the production of myopia, deny any evil effect of concave lenses; furthermore, it is claimed that by restoring the eye to its normal condition of emmetropia, a beneficial influence is exerted upon the progress of the myopia. In support of this view is the clinical fact that with the relief from asthenopia effected by the constant use of glasses, the increase of myopia is frequently checked.

As in hyperopia, so in myopia, no general rule can be given for the prescription of lenses; but there is this difference: in hyperopia correction is not essential so long as the condition gives rise to no disturbance, and the younger the child the less commonly is correction required (excluding strabismus), whereas myopia occurring in childhood requires correction in every instance and at the earliest age compatible with the wearing of spectacles.

In childhood and youth the entire myopia (or at least all but a small fraction) should be corrected and the glasses should be ordered for constant wear. But in myopes who have passed early adult life without correction of their refractive error, the ciliary muscle is untrained and imperfectly developed, and total correction of the myopia will not be tolerated for near work, since the accommodative strain imposed by the lenses is burdensome. The course to be pursued in these cases varies with the degree of myopia and with the attendant circumstances. It is convenient to make the following classification:

1. When the myopia is less than 4 D., and especially if the presbyopic age has been reached, lenses may be used for distance, while near work is performed without the myopic correction.

2. When the myopia exceeds 4 D., vision being binocular, concave lenses are imperative in near work, since without lenses the strain on the convergence is too great to be comfortably and safely endured. The far-point must be so removed by lenses as that no more than 3.5 ma. or 4 ma. of convergence will be required, and usually the lenses should be strong enough to call into play a certain measure of accommodation, such as will incite the proper convergence.

3. When vision is monocular concave lenses are not usually acceptable in near work, since larger images are obtained without these, and without any exercise of accommodation or of convergence. In this class, to which belong the majority of those having myopia of high degree (which has not been corrected in early life), concave lenses are in many cases rejected also for distant vision, or are accepted only for momentary use.

The treatment of muscular disturbances directly dependent upon myopia consists in the application of the appropriate concave lenses, and the earlier the age at which relief is sought, the greater is the likelihood of a successful result. Other measures, which may be required in neglected cases, are described in Chapter XVII.

Secondary Effects of Concave Lenses.—The secondary effects of concave lenses are opposite to those which were noted (Chapter XII.) as occurring in the use of convex lenses. There are chiefly to be considered the prismatic effect, the actual minification of the retinal image, and the apparent minification due to the erroneous judgment as to the distance of the object. There is also alteration in the relation between accommodation and convergence, which may give rise to disturbance when the lenses are first worn; but more frequently this change is advantageous, since insufficiency of convergence is very common in uncorrected myopia.

Use of Tinted Glasses.—Although darkened glasses are not advisable for permanent wear in healthy conditions of the eye tunics, such glasses (No. 1 or 2, London smoke) are sometimes required in the diseased conditions attending high myopia.

Operative Treatment of Axial Myopia.—Because of the disadvantages attending the use of strong concave lenses, with the consequent rejection of them by many myopes of high degree, it was many years ago proposed that the crystalline lens should be extracted for the relief of such persons. Mooren undertook this procedure (1858), but the operation was unsuccessful in his hands, since he extracted the transparent lens without first rendering it cataractous. In consequence of his failure and of the opposition of the two great masters of ophthalmology, von Graefe and Donders, the method fell into ill repute, until in 1887 Fukala revived it by operating successfully in a number of cases. Other ophthalmologists followed Fukala's example and many hundreds of cases have been reported. The operation as now performed consists of two stages; in the first the lens is rendered cataractous by discission, and the second stage consists in removal of the lens through a linear incision. An interval of a few days must elapse between the two stages, the exact time being determined by the condition of the lens and the tension.

While extraction of the lens is a much safer procedure at the present day than it was when Mooren first undertook it for the cure of myopia, yet, owing to the diseased condition of the eye in posterior staphyloma, the operation must always be attended with serious risks, such as hemorrhage and detachment of the retina. This method is, therefore, limited in application. It is especially indicated in those in whom continuance in their occupation is impossible without some greater improvement of vision than can be obtained from

glasses. The operation is contraindicated in old persons; as a rule, forty years should be regarded as the age limit (Fukala), though older persons have been operated on successfully.

The effect of extraction of the lens upon the refractive condition of the eye and upon the size of retinal images varies with the axial length (Chapter VI.). We have learned that if the refracting surfaces are normal in position and curvature, a myopia of about 24 D. will be neutralized by the extraction, and that in this case the linear dimensions of the retinal image will be about one and one-half times as large as in the normal eye. In practice these figures are only approximately correct, since in high myopia there is especial liability to variation in curvature and position of the lens. As the degree of alteration in the refractive condition produced by lens-extraction diminishes with the axial length, the degree of myopia which may furnish emmetropia after extraction varies within quite wide limits. A condition approximating emmetropia may result from extraction in myopia varying from 16 D. to 25 D. Because of the great individual variation, the empiric rules which have been given (as the result of averages deduced from numerous operations) are of no material practical assistance in determining the probable post-operative refractive condition.

In view of the foregoing considerations, it is apparent that operative procedure is contraindicated when vision is so low from macular degeneration that the improvement to be expected from enlargement of images (and in some cases from the removal of an imperfectly transparent and irregularly astigmatic lens) could afford no useful sight. The least degree of myopia in which extraction is permissible is about 12 D., and usually 15 D. is a more appropriate limit.

Operative Treatment of Conical Cornea.—Since only a small proportion of the extremely high myopia

caused by conical cornea would be relieved by extraction, such treatment would be of no material benefit in this affection. In order to ameliorate the distressing condition of the subjects of this disease (lenses being particularly unsatisfactory because of the hyperboloidal form of the cornea), cauterization of the apex of the corneal protrusion has been advocated and practised by ophthalmic surgeons. The excessive curvature is diminished by the flattening which takes place with the process of healing. A subsequent iridectomy may be required on account of the central scar-formation. The operation, as originally practised by von Graefe (abrasion and application of silver nitrate) was not very successful, but with modern electrical appliances great relief has been afforded in a number of cases.[1]

[1] Knapp, Operations Performed in Eye Surgery, Norris and Oliver's System of Diseases of the Eye, vol. iii. p. 824; and Five Cases of Keratoconus Treated with Galvano-cautery, Arch. of Ophth., 1892, p. 540.

CHAPTER XIV.

ASTIGMATISM.

Astigmatism[1] (As.) of the eye was first noted by Thomas Young[2] (1801), who by means of his optometer discovered that he had this defect in his own eye. This consisted in an astigmatism of 1.7 D. (Tscherning), the meridian of greatest refraction being horizontal. Young excluded asymmetry of the cornea in his case by immersing the eye in water (by which means the corneal refraction is almost entirely neutralized), replacing the corneal refraction by that of a convex spherical lens, and observing that the astigmatism remained unchanged. He inferred, therefore, that the defect was due to an oblique position of the crystalline lens. Sir George Airy,[3] who had myopia with astigmatism, first wore spectacles correcting the defect (1827), but the introduction of cylindrical lenses into common use was accomplished through the advocacy of Donders; and practically it may be said that our knowledge of astigmatism dates from the invention of the ophthalmometer by Helmholtz, and from its use by him, by Donders, Knapp, and others.

A slight degree of astigmatism, both regular and irregular, exists in all eyes. Nature only approximates perfection in the development of the body, and one should not expect to find perfect symmetry of the cornea or of the crystalline lens, or perfect uniformity

[1] The definition of astigmatism has been given on p. 104.

[2] Œuvres de Young, edited by Tscherning, p. 125.

[3] Airy, Trans. Cambridge Philos. Soc., 1827, vol. ii.

of index of the lens. The physiological (universal) astigmatism which results from slight imperfection is not noticeable in ordinary vision, but when one looks at a point of light, as a star, the image on the retina is not a point, as it would be if the eye were perfect; owing to irregular astigmatism, the star appears as a bright centre with lines of light (rays) proceeding in various directions from this centre. The more free an eye is from astigmatism the less marked is the ray-like appearance; but that such appearance is wellnigh universal is attested by the time-honored custom of picturing a star, not as a round body, but as sending forth streams of light in various directions.

The asymmetrical curvature to which regular astigmatism is due lies chiefly in the cornea, though the crystalline lens is not entirely free from this defect. Since oblique spherical refraction is astigmatic, an eccentric position of the cornea or of the lens, or an oblique position of the latter, produces regular astigmatism.

Etiology of Corneal Astigmatism.

Regular corneal astigmatism is due, in the vast majority of cases, to asymmetrical development of the eyeball—a defect which is usually congenital, though it is sometimes acquired in postnatal growth. We have learned that in those eyes which may be regarded as normal the curvature of the cornea is, as a rule, slightly greater in the vertical than in the horizontal meridian. In assuming this form the cornea follows that of the eyeball, which is slightly shorter in the vertical than in the horizontal diameter; and this, in turn, conforms to the shape of the orbit, which offers its least dimension in the vertical meridian. Exaggeration of this normal asymmetry gives rise to astigmatism in excess

of the amount which can be regarded as physiological.

Relation of Astigmatism to Cranial Development.—But the foregoing explanation serves only for such asymmetry as presents the greatest curvature in the vertical meridian. Not infrequently the cornea presents its least curvature in the vertical meridian, the greatest curvature being in the horizontal meridian, or the meridians of greatest and least curvature may be neither vertical nor horizontal (oblique). An attempt has been made to prove that all such astigmatism (and, in fact, that all congenital astigmatism) occurs in connection with and results from faulty or asymmetrical development of the cranium.[1] While this connection cannot be universally verified, it is a matter of common observation to find a high degree of astigmatism coexisting with defective cranial development.

Post-natal Change in the Form of the Cornea.—The cornea attains its full growth at an early age—about the third year. In accordance with this fact, keratometric observations which have been repeated upon the same persons after the lapse of a number of years show that very little change takes place in the form of the cornea after it has attained its growth.[2] Exceptionally, however, measurements have revealed a decided asymmetry in a cornea which had previously been found free from this defect. When no other cause can be adduced, such change of form may be ascribed to pressure upon the cornea by the eyelids, to tenotomy or advancement of an extra-ocular muscle, or to asymmetrical increase in the size of the eyeball.

[1] de Wecker, Comptes Rendus de la Soc. d'Anthropologie de Paris, 1868, and Landolt, Relations between the Conformation of the Cranium and that of the Eye, Brit. Med. Journal, April, 1881.

[2] Pfalz states, as the result of a number of measurements, that the cornea undergoes a gradual change from youth to old age, so that at the latter period of life the greatest curvature is not as a rule vertical, but horizontal. Archives of Ophth. (Report of Ninth Internat. Ophth. Cong., Utrecht), 1899, p. 665.

But the only common cause of change in the form of the cornea is the interposition of scar-tissue, either as the result of disease (suppuration) or of traumatism (corneal section). In the former case the astigmatism is, for the most part, irregular; but with this a certain amount of regular astigmatism, capable of correction, may also occur. A high degree of regular astigmatism is the rule after corneal section, as in cataract-extraction. This is due to overriding of the lips of the wound with the interposition of scar-tissue, thereby diminishing the curvature in the meridian at right angles to the section.[1] The alteration in curvature is greatest immediately after the operation, and gradually diminishes, sometimes vanishing entirely, but usually a certain portion is permanent. After the lapse of six months no further change is to be expected.

Effect of the Posterior Corneal Refraction in Astigmatism.—In order to determine this it is necessary to measure the curvature of both anterior and posterior surfaces. From these measurements the total corneal astigmatism may be calculated. As this is a tedious process and not practicable in clinical work, it is fortunate that the effect of the posterior corneal refraction is, in great part, neutralized by assigning to the cornea the index of the aqueous humor (1.337), as is done in keratometry.

We may assume that the posterior surface generally follows the form of the anterior surface; and as the posterior corneal refraction is divergent while that at the anterior surface is convergent, it is clear that the posterior corneal astigmatism must exert a neutralizing action upon that which occurs at the anterior surface. But, as above stated, this neutralizing action is included in the keratometric record, with

[1] According to Pflueger, who has made a number of measurements before and after operation, the curvature is sometimes increased by the corneal section. Annales d'Oculistiques, 115, p. 460.

the exception of a slight excess of divergent action not so included. Hence, to some extent, and the more so as the posterior exceeds the anterior asymmetry, posterior corneal astigmatism exerts a compensatory action upon that which is recorded by the keratometer. The greatest compensatory action which has been attributed to this cause is 1 D. in a total astigmatism of 6 D. (A. Javal).[1]

Etiology of Lenticular Astigmatism.

As with the posterior surface of the cornea, so the effect of the crystalline lens in the production of astigmatism can be ascertained only after complicated calculations, which are altogether disproportionate to the usefulness of the knowledge gained thereby. Such measurements as have been made indicate that the lens is a subordinate factor, except in the lowest grades of astigmatism. This is also in agreement with the evidence afforded by keratometry, which shows that, ordinarily, regular astigmatism can be ascribed to asymmetry of the cornea. Not only are the lenticular surfaces less inclined to asymmetry than is the cornea, but, owing to the greater refractive power of the latter, a certain amount of asymmetry produces more astigmatism than does the same asymmetry of the crystalline lens.

Regular lenticular astigmatism is usually attributed to an eccentric or oblique position of the lens. Tscherning's investigations indicate that in the normal eye the lens is slightly inclined to the optic axis, the position being such as if the lens were rotated about its vertical axis. In this condition the meridian of greatest refraction must be horizontal. Since the meridian of greatest corneal refraction is, as a rule, vertical, it is evident that the oblique position of the

[1] Javal, Ophthalmometry, in Norris and Oliver's System of Diseases of the Eye, vol. ii. p. 137.

lens must tend to neutralize the corneal astigmatism. When, however, the meridian of greatest corneal refraction is horizontal, the normal lenticular astigmatism increases the astigmatism caused by the corneal asymmetry. The astigmatic effect due to this oblique position of the lens is usually slight, varying from 0.25 D. to 0.75 D. (Tscherning). If it exceeds this limit the obliquity of the lens must be regarded as abnormally great.

Sometimes, when there is marked deformation of the eyeball, as in high corneal asymmetry, the asymmetrical development affects also the crystalline lens. In this case the astigmatic action of the lens must increase that produced by the cornea. Hence, the total astigmatism may exceed the degree recorded by the keratometer, although this instrument registers too high a degree in the measurement of the corneal astigmatism.

Regular lenticular astigmatism *arising after birth* is usually due to obliquity of the lens (from partial dislocation) as the result of traumatism or disease.

Irregular lenticular astigmatism is caused by lack of uniformity of refractive index or of curvature in the various component segments of the lens, and in the various parts of these segments. This is a defect which is common to all eyes; but marked irregular lenticular astigmatism occurring later in life indicates the presence of pathological changes which eventually lead to the formation of cataract.

Hypothesis of Dynamic Lenticular Astigmatism.—Astigmatism produced by partial (asymmetrical) contraction of the ciliary muscle for the purpose of correcting an opposite corneal astigmatism is a question about which opinions differ. The hypothesis of dynamic compensatory astigmatism was first announced by Dobrowolsky[1] (1868), who based his opinion upon

[1] Dobrowolsky, Archiv für Ophth., 1868, xiv., 3, p. 51.

observations and experiments made by him. Following him, many others, as the result of clinical or experimental observation, were led to accept his conclusions. With the introduction of clinical keratometry, compensatory astigmatism was assigned by Javal as a potent factor in causing the discrepancy between the keratometric record and the subjective astigmatism.[1] Supported by these authorities, the hypothesis has been widely accepted. The amount of compensatory action which has been assigned to the ciliary muscle varies, according to different authorities, between 1 D. and 3 D.

Among those who believe that compensatory action of the ciliary muscle does not occur are G. J. Bull[2] and Hess.[3] They, having carefully reviewed the published cases of asymmetrical contraction, have shown that in all of them certain evident sources of error were not excluded. There must be considered, as of the utmost importance in reaching a correct conclusion, the ability of the individual to decipher diffusion-images, the inability to discriminate between perfectly sharp images and those formed with slight diffusion, the stenopæic effect of partially closing the lids, and the variation in the size of the pupil, especially in comparing the tests of vision with cycloplegia and without it.

Having eliminated these sources of error, Hess proceeded to determine by experiment whether or not partial accommodation is possible. His device consisted essentially of two cotton threads stretched at right angles to each other. The stands supporting the threads were movable along a graduated rod. The astigmatism (natural or artificial) of the person

[1] Javal, Memoires d'Ophthalmometrie.

[2] Bull, Annales d'Oculistiques, 1892, 107, p. 109.

[3] Hess, Archiv für Ophth., 1896, xlii. 2, p. 80. Here also will be found references to the literature of this subject.

under examination being known, the vertical thread, for instance, was placed at the near-point of the horizontal meridian of the eye, while the horizontal thread was placed at the near-point of the vertical meridian. By this arrangement both threads must appear distinct to the eye undergoing examination. By moving one of the threads, the power of the eye to accommodate in one meridian could be ascertained. Having examined in this way twenty-three individuals, Hess found that in no case could the highest possible partial contraction exceed 0.37 D., and it was often less than 0.1 D.[1]

Although it is possible that contraction of the ciliary muscle may, in certain instances, be more effective in one meridian than in another, yet the existence of a power to control this action in any required meridian, as for the correction of corneal astigmatism, implies the existence of a separate nerve-nucleus for each principal meridian—which, to say the least, is highly improbable.[2]

Degree of Astigmatism.

The degree of regular astigmatism varies from an inappreciable amount to 15 D. or more. In a few instances only has an amount reaching the latter degree (15 D.) of congenital astigmatism been recorded. Astigmatism of 20 D. may occasionally be measured with the keratometer shortly after the healing of corneal section, only a minor portion of which, however,

[1] It was not demonstrated that this amount of partial contraction existed, but it could not be excluded by the test.

[2] Nevertheless, cases occasionally occur in which corneal astigmatism is masked (even under cycloplegia) by an opposite lenticular astigmatism, which gradually disappears with advancing age, so that the subjective astigmatism becomes correspondingly greater. No satisfactory explanation of this has been found.

is permanent. With the exception of such, an amount exceeding 6 D. is of infrequent occurrence.

Donders and others of the older ophthalmologists regarded astigmatism of less than 1 D. as physiological and as not requiring correction; but at the present day 0.25 D. and, by some, even 0.12 D. (which may be found in almost every eye) is considered to call for correction in certain cases.

Classifications of Astigmatism.

Classification with Reference to the Form of the Cornea.—Since the meridian of greatest curvature of the cornea is, *as a rule*, vertical or nearly so, the astigmatism which results from this kind of asymmetry is called *astigmatism with the rule*.

When, as sometimes is the case, the meridian of greatest curvature is horizontal, the astigmatism is said to be *against the rule, or inverse*. The astigmatism which results from the ordinary corneal section (upward) for cataract-extraction must be inverse, since the section diminishes the vertical curvature without materially altering the horizontal curvature.

Oblique astigmatism is that in which the principal meridians are not vertical and horizontal (or nearly so), but make angles of 45 degrees (approximately) with the vertical and horizontal lines. The limit between astigmatism with the rule or against it and oblique astigmatism, as thus defined, is arbitrary; but it is customary to regard astigmatism as oblique when the principal meridians are more than 25 degrees from the vertical and horizontal lines.

Classification with Reference to the Relative Directions of the Principal Meridians in the Two Eyes.—In the majority of persons astigmatism in the two eyes is *symmetrical;* that is, the meridians of great-

est and least curvature correspond in the two eyes. If, for instance, the meridian of greatest curvature is vertical in one eye, we may expect it to be vertical in the other eye also. If the upper extremity of the meridian of greatest curvature lies on the temporal side of the vertical meridian in the right eye, it also lies, if the astigmatism is symmetrical, on the temporal side in the left eye, the angle of inclination being the same in the two eyes. If the meridian of greatest curvature is denoted by 30 degrees on the ordinary (parallel) scale (Fig. 58) in the left eye, the symmetrical meridian in the right eye is denoted by 150 degrees; but if the bisymmetrical scale (Fig. 59) is used, the angular markings are the same in the two eyes.

When the meridian of greatest curvature (not being vertical or horizontal) is marked by the same angle (parallel scale) in the two eyes—that is, when the meridian of greatest curvature is inclined toward the temple in one eye and toward the nose (to an equal degree) in the other—the astigmatism is said to be *asymmetrical* but *homologous*.

When the meridians of greatest curvature in the two eyes are neither symmetrical nor homologous, as, for instance, when one eye presents the greatest curvature in the vertical meridian and the other in the horizontal meridian, the astigmatism is *asymmetrical* and *heterologous*. This kind of astigmatism is uncommon.

Classification with Reference to the Relation between the Position of the Retina and that of the Focal Lines.—*Simple hyperopic astigmatism* (H. As. or Ah.) is that in which, the accommodation being relaxed, one focal line falls upon the retina while the other lies behind it; or, it is that in which the eye is emmetropic in one principal meridian and hyperopic in the other.

Compound hyperopic astigmatism (H. As. Co. or H. + Ah.) is that in which both focal lines lie behind

the retina; the eye is hyperopic in both principal meridians, but more so in one than in the other.

Simple myopic astigmatism (M. As. or Am.) is that in which the eye is emmetropic in one and myopic in the other principal meridian.

Compound myopic astigmatism (M. As. Co. or M.+Am.) is that condition in which the eye is myopic in both principal meridians, but more so in one than in the other.

When in compound astigmatism the hyperopia or myopia is relatively so great as to outweigh (in importance) the astigmatism, the condition is more appropriately designated as *hyperopia* or *myopia with astigmatism.*

Mixed astigmatism (Ah.+Am.) is that in which the eye is hyperopic in one meridian and myopic in the other.

Since the kind of astigmatism, in accordance with this classification, depends upon the length of the antero-posterior diameter of the eyeball, it not uncommonly happens that compound hyperopic astigmatism passes by degrees into simple hyperopic, mixed, simple myopic, and compound myopic astigmatism, with the increase in diameter of the eye, as the result of growth or disease.

Symptoms of Astigmatism.

Of subjective symptoms, subnormal vision, asthenopia, and headache are the most characteristic. These are, however, not pathognomonic, for each may follow eye-strain from some other cause.

Vision in Astigmatism.—In the mildest grades of astigmatism vision may not be below normal ($\frac{6}{6}$), and it may even surpass this; but in moderate and high-grade astigmatism vision is always defective. The visual power varies, as in other anomalies, under different conditions, and especially with variation in size

of the pupil. The latter is a very important consideration, since keratometry shows that corneal asymmetry and irregularities increase rapidly with increase of distance from the corneal summit. In this way is explained the frequent manifestation of greater astigmatism when the examination is conducted under mydriasis than is shown without it.

The question arises as to what is the most favorable relation between the retina and focal lines—that which the individual will, so far as possible, seek either by exercise of accommodaton or by change in position of the object of vision. In answer to this question, Javal has stated, as the result of his investigations, that an astigmatic person obtains his best vision when the object is conjugate to the retina in the horizontal meridian; that is, when the vertical focal line falls upon the retina.

Two advantages arise from this relation : 1. While horizontal lines are more or less blurred, all vertical lines are distinct; and experiment shows that, in reading, distinctness of the vertical strokes of the letters is of more moment than distinctness of the horizontal strokes. 2. The object being in focus in the horizontal meridian, rays of light which would enter in the vertical, ametropic meridian can be largely excluded by partially closing the lids—a device to which all astigmatics of high degree resort, and by which great improvement of vision is gained, and especially when the eye is properly adapted in the horizontal meridian.

Reymond and others believe that astigmatic vision is preferably accomplished, not as suggested by Javal, but by adapting the eye first in one and then in the other principal meridian, and that by a rapid change in accommodation a composite mental impression is obtained.[1] That this rapid change of accommodation

[1] Reymond, Annali di Ottalmologia, xvi. p. 498.

may take place in the lowest grades of astigmatism and for a short period (as when undergoing examination with a test-card) is possible, but that it should be maintained for any length of time (as in reading) or in high astigmatism is incredible.

Javal's theory of astigmatic vision is opposed also by Hess,[1] who believes that the maximum vision is obtained not when the eye is adapted in either principal meridian, but when it is so adapted that the retina lies (between the two focal lines) where the intercepted image is free from distortion and where all lines appear equally distinct. That the larger letters of the test-card are rendered more evenly visible by placing before the eye such a lens as will place the retina in this position, there is no doubt; but it cannot be maintained that smaller letters can be read with this lens than when the eye is adapted in the horizontal meridian.[2]

The most unfavorable position of the retina for reading is, according to Javal's theory, such that the letters are in focus in the vertical meridian. The vertical strokes of the letters are then blurred and the horizontal strokes are distinct; every point of every letter forms on the retina a horizontal line, and the horizontal diffusion-image of one letter overlaps that of the adjacent letter, so that the reading of small, closely set type is impossible.

The most favorable position of the retina—adaptation in the horizontal meridian—is possible for distant vision only when the eye is emmetropic in the horizontal meridian or hyperopic with sufficient accommodative power to overcome the hyperopia.

The most unfavorable relation—adaptation of the vertical meridian—cannot be avoided in distant vision

[1] Hess, loc. cit.

[2] This, at least, is the author's conclusion as the result of a number of experiments, which showed that maximum vision resulted when the vertical lines were rendered distinct.

when the eye is emmetropic in the vertical meridian, and, in the horizontal meridian, either myopic or hyperopic without accommodative power to render it emmetropic at the expense of the vertical meridian.

In *near vision* the most advantageous adaptation will be accomplished, so far as possible, by change in position of the object and by exercise of accommodation.

Vision in Irregular Astigmatism.—In pathological irregular astigmatism defective vision is a constant and characteristic symptom. Objects appear distorted, and sometimes there is monocular diplopia or polyopia. The latter is especially common in irregular lenticular astigmatism occurring as a precursor of cataract.

Double or triple monocular vision is not uncommonly observed in ametropia, disappearing with the correction of the ametropia by a suitable lens.[1] Such multiple vision is usually due to slight difference in index of the three main segments of the crystalline lens, so that each segment gives rise to a separate retinal image of an object. In emmetropia these images are so nearly superposed that they are fused as a single image; but when the retina is remote from the position of the average focus (just as in Scheiner's experiment), vision is multiple. This is a frequent symptom in hysterical spasm of the accommodation (Parinaud[2]).

Asthenopia.—Astigmatics more often complain of this symptom than of defective vision. This is especially so as regards the large number of eye-workers—students, accountants, and artisans—that civilization has produced. As with other refractive anomalies, the asthenopia bears no fixed relation to the degree of astigmatism; it depends rather upon the state of health and the character of the work pursued.

[1] Bull, G. J. The Visual Defects of Refractive Error, Trans. Ophth. Society, Un. K., xvi. p. 200.

[2] Parinaud, Ocular Manifestations of Hysteria, Norris and Oliver's System of Diseases of the Eye, vol. iv. p. 738.

Headache in astigmatism, as in hyperopia, occurs usually in conjunction with asthenopia, but it sometimes occurs without other symptoms pointing to refractive error.

Asthenopia and headache occurring in hyperopia may usually be ascribed to exhaustion of the ciliary muscle (accommodative asthenopia); in myopia these symptoms are assigned to disturbance in the relation between accommodation and convergence (muscular asthenopia); in astigmatism either or both of these kinds of asthenopia may arise, but, doubtless, the main source of disturbance is nerve-exhaustion (retinal asthenopia) resulting from the mental effort to interpret diffusion-images. It is also possible that in oblique astigmatism asthenopia may arise from the tax imposed upon the oblique muscles in their effort to obliterate distortion by rotating the meridians of the eye, as is maintained by Savage.[1]

Objective Symptoms.—*The pathognomonic objective symptoms* of astigmatism have already been considered in dealing with objective optometry. In addition to these there are conjunctival congestion (occurring especially after close application of the eyes), chronic conjunctivitis, blepharitis, and congestion of the optic nerve and retina, all of which occur also in other conditions.

Diagnosis of Astigmatism.

The methods of estimating the degree of astigmatism have been given in Chapter XI. The order of applying these tests which has been recommended for other refractive errors may advantageously be followed also in astigmatism.

The degree and the situation of the principal meridians of the corneal astigmatism can be quickly deter-

[1] Ophthalmic Myology, p. 323.

mined by keratometry. The disadvantages of keratometry are that it fails to reveal the total astigmatism and the concurrent refraction—whether hyperopic, mixed, or myopic.

In deducing the total astigmatism from the result of keratometry, it is empirically assumed (in accordance with practical experience) that 0.50 D. (or 0.75 D.) must be subtracted from the corneal astigmatism or added to it, according as this is with the rule or against it. If, for instance, the keratometer indicates 0.50 D. of corneal astigmatism with the rule, the probability is that the eye as a whole is free from astigmatism; if, on the other hand, this amount of corneal astigmatism is against the rule, the probable total astigmatism is 1 D. The reason of this is to be found in the frequent occurrence of slight lenticular astigmatism against the rule.

This relation between the corneal and lenticular astigmatism is, however, by no means constant, and therefore the keratometer is of little value in the accurate estimation of slight astigmatism (less than 1 D.) which so frequently gives rise to asthenopia in eye-workers. In the higher degrees of corneal astigmatism the error which is likely to arise from the lenticular astigmatism is proportionally less, but two other factors of uncertainty must then be considered. These are (1) the registration of too high a degree of corneal astigmatism because of spherical aberration, and because the images of the mires are reflected from points on the cornea beyond the usual pupillary area; and (2) the participation of the lens in the same kind of asymmetry as that which affects the cornea. The overestimation of the total astigmatism due to the former factors is to an uncertain extent counteracted by the latter.

It should also be remembered, in estimating the power of the correcting lens, that the keratometer

measures the astigmatism at the surface of the cornea, while the lens must be placed about 15 mm. in front of this surface, thus rendering necessary a weaker convex or a stronger concave lens than as measured at the surface of the cornea.

Skiascopy possesses the advantage that it reveals very accurately the total astigmatism and at the same time the refraction of the eye in the principal meridians. It is of especial value in young children, in whom astigmatism demands correction prior to the age at which keratometry or subjective examination with lenses is possible.

After completion of the objective examination, a careful subjective examination with trial lenses must be conducted. In this examination the indications for cycloplegia are the same as in other refractive errors, for it is to ascertain what degree of hyperopia or myopia is associated with the astigmatism that the cycloplegic is employed. It is important to note any discrepancy between the astigmatism as estimated with cycloplegia and without it. The manifestation of a higher degree when the pupil is dilated by the cycloplegic usually indicates that the asymmetry is greater peripherally than near the axis. Since in normal vision the peripheral portion of the cornea is excluded, the estimate made without cycloplegia, if corroborated by other tests, is that which should be adopted for the correcting lens.

Treatment of Astigmatism.

The treatment of regular astigmatism consists in the correction of the defect by means of a suitable cylindrical or toric lens. In the lower grades correction should embrace the entire error, but in high astigmatism total correction will often not be tolerated until weaker lenses have first been worn for some time.

The reason for this is to be found in the distorting property of asymmetrical lenses. Annoyance from this cause is usually of short duration in young persons, but elderly persons who have not at an earlier age become accustomed to asymmetrical lenses sometimes decline to accept correction of their astigmatism; this is especially liable to occur in oblique astigmatism.[1]

The apparent distortion of objects by asymmetrical lenses is due partly to the actual distortion of the retinal image, and partly to the effect exerted by the change in accommodation upon binocular visual perception. The former has been described in Chapter VII. (p. 106); the explanation of the latter is the same as that for spherical lenses, for which reference may be made to the chapter on Hyperopia (p. 237). Of the distorting effect upon binocular vision caused by placing an asymmetrical lens before only one eye, or a much stronger lens before one eye than before the other, mention will be made in the chapter on Anisometropia.

In astigmatism of high degree the correcting lenses must be ordered for constant wear, and preferably so in all astigmatism exceeding 1 D. When the astigmatism is less than 1 D., it suffices in some cases to wear the glasses only during near work, while in others asthenopia will be relieved only if the glasses are worn constantly.

In the correction of astigmatism it not infrequently happens that an eye which, under the influence of a cycloplegic, exhibits simple hyperopic astigmatism, will, after the ciliary muscle has regained its tone, require the addition of a concave spherical lens to the astigmatic correction. For instance, an eye may require a +0.50 D. cylindrical lens during cycloplegia

[1] Savage believes this to be due to the unaccustomed torsion by the oblique muscles in their effort to obliterate distortion.

but after the effect of the drug has passed away a —0.50 D. spherical lens must be added; or it may require a cylindrical lens of +1 D. during cycloplegia, whereas the proper correcting lens may be a combination of this lens with a —0.50 D. spherical lens.

Prescription of Compound Lenses.—Since it is the duty of the optician to provide lenses exactly as called for by the prescription of the oculist, the latter must, in ordering correction for hyperopia or myopia associated with astigmatism, make use of the knowledge gained in the study of asymmetrical refraction, so that every combination of lenses may be reduced to its simplest form, or to such other form as may be deemed preferable. Thus in the first example, in which a —0.50 D. spherical lens is combined with a +0.50 D. cylindrical lens, the prescription should call for a simple —0.50 D. cylindrical lens having its axis at right angles to that of the convex lens.

In the second example, suppose the axis of the cylindrical lens to be at 90 degrees. Then the prescription for the combination would naturally be written —0.50 D. sph. +1 D. cyl., ax. 90. But if the test had been made with two cylindrical lenses, the result would have been expressed by the combination —0.50 D. cyl., ax. 180, +0.50 D. cyl., ax. 90. Again, if in the application of the test the horizontal meridian had first been corrected by a +0.50 D. spherical lens, a —1 D. cylindrical lens would have been required to correct the astigmatism. In this case the prescription would call for +0.50 D. sph. —1 D. cyl., ax. 180. The refractive effect of each of these combinations is identical, since in each the vertical refractive error is expressed by —0.50 D., and the horizontal by +0.50 D. The question, therefore, arises as to which is the most suitable combination. The second, or *crossed cylinder*, may be excluded because it possesses no advantage and is more difficult of con-

struction. In the choice between the other two combinations, it would, in this instance, be of no moment which might be selected; but in general the simplest combination (that which would give the least weight) should be selected. For instance, the combination +2 D. sph. —3 D. cyl., ax. 180, should be replaced by its simpler equivalent, —1 D. sph. +3 D. cyl., ax. 90, since in this the spherical curvature is less than in the former and, therefore, the lens can be made of thinner glass.

Periscopic Property of Concave Lenses.—In order to make use of this property the optician always places the concave surface toward the eye, and in such manner that, as far as the prescription permits, the periscopic effect is obtained in the horizontal meridian, thereby allowing greater freedom of lateral rotation of the eyes. In the former of the above-cited combinations, the axis of the cylindrical element being horizontal, no periscopic effect would be obtained in this meridian. If, however, the axis of this lens were vertical, greater periscopic effect would be gotten from this than from the second combination; but at the expense of greater weight. When, in such cases, the periscopic action is especially desired, toric lenses are preferable.

We notice that in each of these combinations a convex lens is combined with a concave lens; this cannot be avoided, since the refraction of the eye is hyperopic in one and myopic in the other principal meridian. But if we should derive, as the result of examination, the combination +3 D. sph. —1 D. cyl., ax. 180 (the cylindrical being less than the spherical element), the astigmatism is not in reality mixed; the refraction is properly expressed by the combination +2 D. sph. +1 D. cyl., ax. 90, and this is the form in which the order should be written.

Prescription of Toric Lenses.—In ordering toric lenses the prescription may be written as a sphero-cylinder,

with the statement that the lens is to be ground as a torus; or we may write, for example: "Toric, +2 D., ax. 180 +3 D., ax. 90. Make on 6 D. curve." In filling this prescription the optician would select a plano-toric lens having a convexity of 6 D. in the vertical and of 7 D. in the horizontal meridian. He would then grind a spherical concavity of 4 D. on the plane side of the lens, thus obtaining the proper refractive effect and at the same time rendering the lens periscopic. The marked periscopic effect which can thus be gotten in toric lenses is a decided advantage, but the resulting external convexity is cosmetically objectionable.

Similarly, if it is desired to order a double convex sphero-toric lens after cataract extraction, there being 10 D. of hyperopia complicated with 2.50 D. of inverse astigmatism, the prescription may be written: "Toric, +10 D., ax. 90 +12.50 D., ax. 180. Make on 6 D. curve." This would call for a lens having on one face a toric convexity of 6 D. in the horizontal meridian and of 8.50 D. in the vertical combined with a spherical convexity of 4 D. on the other surface.

Surgical Treatment of Astigmatism.—Because of the discomforts which arise from the use of strong asymmetrical lenses, it has been proposed to overcome regular astigmatism by surgical means. This consists in making corneal incisions or galvano-cauterizations at right angles to the meridian of greatest curvature, since with the healing of the wound the curvature is lessened.[1] But the impossibility of regulating the result renders it improbable that this method will come into practical use.

Treatment of Irregular Astigmatism.—Irregular astigmatism is practically a hopeless condition; but in

[1] Bates, W. H. Arch. of Ophth., vol. xxiii. p. 9, and Pflueger, Annales d'Oculistiques, 115, p. 460.

an eye deformed by corneal cicatrices there is often associated a certain degree of astigmatism which is capable of improvement by a cylindrical lens. This should always be carefully sought, in order that the patient may have the advantage of any possible improvement. Occasionally vision may be improved by an iridectomy, thus permitting light to enter through a less irregular portion of the cornea.

CHAPTER XV.

ANISOMETROPIA.

Knowing how slight a change in curvature or length of axis causes an appreciable change in refractive condition, one should scarcely expect this condition to be exactly the same in any pair of eyes; yet in many persons the difference is too slight to be determined, even with the exact methods of examination which are at our command.[1] Such eyes are said to be *isometropic*. But in a large proportion of persons there is more or less determinable difference of refraction in the two eyes, and this condition is called *anisometropia*.

While isometropia is the standard or ideal condition, as is emmetropia, and as slight deviation from emmetropia does not constitute a real anomaly, so slight anisometropia is not to be regarded as a pathological state. In other words, anisometropia is a defect only when it is sufficient to cause some disturbance, either visual or nervous. The least refractive difference which may be so classed cannot be definitely stated, because this varies with the refraction in the two eyes. For instance, if one eye is emmetropic while the other has 2 D. of myopia, there should be no hesitation in classing the anisometropia as a defect, capable of

[1] A variation of 1 D. in the refraction of the eye corresponds to a variation of $\frac{1}{6}$ mm. in the radius of the cornea (as shown by the keratometric scale) or to a variation of $\frac{1}{3}$ mm. in axial length (p. 223).

giving rise to very great disturbance; but if one eye has 9 D. and the other 11 D. of myopia the same anisometropia (2 D.) is a subordinate factor.

Anisometropia signifies nothing as to the state of refraction in either eye. One eye may be emmetropic and the other hyperopic or myopic; one eye may be hyperopic and the other myopic (*antimetropia*); both eyes may be hyperopic or myopic, the degree of error not being the same in the two eyes; or one eye may be astigmatic, or there may be a greater degree of astigmatism in one eye than in the other.

Etiology.—Anisometropia may be either congenital or acquired, being more frequently congenital and due to defective development, with or without involvement of the corresponding half of the cranium. Acquired anisometropia results from extraction or luxation of the crystalline lens; from alteration of corneal curvature, produced by ulceration or corneal section; from elevation of the retina in partial detachment; or from unequal post-natal increase in size of the eye, as from progressive myopia.

Vision in Anisometropia.—Vision in anisometropia may be accomplished in one of the three following ways: (1) There may be binocular vision; (2) vision may be monocular, either eye being used alternately, or (3) vision may be monocular, one eye being used to the exclusion of the other.

Binocular Vision in Anisometropia.—It having been ascertained by means of the stereoscope or otherwise that an anisometrope possesses binocular vision, the question arises as to the manner in which such vision is accomplished; whether by exercising a greater amount of accommodation in one eye than in the other, thus equalizing the refraction, or by the mental fusion of the clear image as formed in the adapted eye with the blurred image as formed in the other. The latter and commonly accepted view was disputed in 1889 by

Fick,[1] who cited a number of cases in evidence of his opinion that the refraction is equalized by unequal action of the ciliary muscle. This theory, which has also been advocated by Schneller,[2] is opposed by Hess,[3] who from a number of experiments concludes that there is no evidence in favor of unequal accommodation in the two eyes. This question is similar to that of dynamic compensatory astigmatism (p. 276); there is no reason for believing that the ciliary muscle of one eye can be innervated alone, or that when both muscles are innervated, one can receive a designedly greater impulse than the other.[4]

In accordance with the foregoing conclusions, it follows that if both eyes have the same visual acuity, the eye which requires the less accommodation will play the more important part in vision, the blurred image of the second eye being a secondary factor, though one of no little value in stereoscopic vision.

Alternate Vision in Anisometropia.—This generally occurs when one eye is emmetropic or nearly so, the other eye having 3 D. or 4 D. of myopia, and both eyes having good visual acuity. Though deprived of stereoscopic vision, the anisometrope who sees in this way enjoys a certain advantage, in that he has good distant vision and yet does not require reading glasses, even though he may have passed the presbyopic age, since the emmetropic eye serves for distant and the myopic eye for near vision.

[1] Eugen Fick, Arch. für Augenheilkunde, xix. and xxxi.; Arch. für Ophth., xxxviii., 3.

[2] Schneller, Arch. für Ophth., xxxviii., 1.

[3] Hess, Arch. für Ophth., xxxv., 3, and xxxviii., 3.

[4] It may happen, however, from an unequal receptivity (irritability) of the ciliary muscles that stimulation of the accommodation-centre may give rise to greater contraction of the muscle in one eye than in the other, as is artificially effected by the instillation of eserin in one eye. Similarly, it may be possible that because of unequal sclerosis the same impulse may produce a greater change in curvature of the lens in one eye than in the other.

Monocular Vision, One Eye Being Permanently Excluded.—Vision is accomplished in this way usually when, in addition to the anisometropia, one eye is materially below its fellow in visual power. Strabismus, either convergent or divergent, is the common accompaniment of this condition, convergence being of more frequent occurrence in hyperopia, while divergence is the usual condition in myopia.

Anisometropic Asthenopia.—Since any kind of refractive error is capable of giving rise to asthenopia, it is ordinarily impossible to discriminate between asthenopia due to this cause and that which is directly referable to the inequality of refraction in the two eyes; but that this inequality is of itself capable of producing asthenopia is attested by occurrence of the latter in cases in which one eye is emmetropic and the other slightly myopic (1 D. or 2 D.), provided there is binocular vision, while no such symptoms occur if the emmetropic eye is used for distance and the myopic eye for near work.

Anisometropic asthenopia is due to nerve-exhaustion in the effort to maintain binocular vision under disadvantageous conditions. Not only is there indistinctness of the image in the unadapted eye, but the images in the two eyes are unequal in size. This inequality may be slight and due chiefly to the diffusion on the retina of the light in the unadapted eye, or the inequality may be very great, as when one eye has been rendered aphakic by the extraction of its cataractous lens.

When anisometropia has existed since birth, the eyes may never have learned binocular vision, one eye having passed into a state of strabismus at an early age; or, if binocular vision exists, the nervous mechanism may have become adapted, by training, to the inequality of images. But even in this most favorable condition asthenopia may arise at any time, as when a

special tax is thrown upon the eyes, or when the bodily vigor is reduced from any cause.

Treatment.—In the majority of eyes which require the services of an oculist the ametropia of one eye will be found to differ slightly from that of the other eye; in all such cases the correction appropriate for each eye should be ordered. It should be our aim also to give the appropriate correction for each eye and thus to restore the normal relationship, when the dissimilarity is more marked; but, unfortunately, many persons will not tolerate such correction.

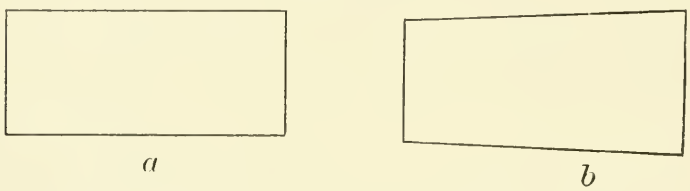
The explanation of this intolerance is found partly in the nerve-disturbance produced when an eye which has previously acted only a subordinate part in vision is suddenly put in condition to co-act with its fellow, and partly in the secondary effects of lenses, such as have been described in previous chapters. In axial ametropia a lens worn at the anterior focus of the eye produces a retinal image equal in size to that formed in emmetropia; hence if both eyes are properly corrected, the images in the two eyes should be of equal size. The disturbance cannot, therefore, be produced in this case by unequal images; it is due to the change from the condition to which the person has become accustomed by lifelong association.

In astigmatism the proportions of the retinal image are changed by the correcting lens, but the image cannot be made to conform to that in the emmetropic eye; hence, in monocular astigmatism a double difficulty must be overcome when the correcting lens is applied.

The apparent alteration in size of an object, which has been previously explained (p. 237), produces in anisometropia a one-sided disturbance. This is sometimes a source of great annoyance in persons (architects, mechanics, etc.) who have to deal with the rectangular form of objects. If a rectangular figure,

such as is illustrated in Fig. 75 (*a*), is placed in front of and equidistant from the two eyes and viewed binocularly with a convex spherical lens before the right eye, the rectangular form of the object will be lost, the right side appearing broader than the left, as illustrated in Fig. 75 (*b*). If a concave lens is substituted for the convex lens, the right side of the figure appears smaller than the left. This illusion arises from the fact that the right eye is chiefly concerned in looking at the right side of the object, while the left eye is the more important as regards the left side of the figure. But that the actual change in size of the retinal image is not the sole cause of this phenomenon is shown by the substitution of a cylindrical for the spherical lens.

FIG. 75.



a *b*

A cylindrical lens produces the same effect as the spherical lens when the axis is vertical, there being in this case no vertical alteration of the image, while it produces the opposite effect when the axis is horizontal. Hence we must conclude that the apparent alteration is due to disturbance of accommodation : the effort of accommodation which adjusts the naked eye for the left side of the figure is more than sufficient for the right eye, having a convex lens before it; consequently, the impression is received that the right side is farther away and larger than the left side. Similarly, with the concave lens before the right eye the right side of the figure seems to be nearer and smaller than the left side. The peculiar effect of the cylindrical lens is also explained partly by the influ-

ence which it exerts over accommodation and partly by the actual distortion of the image on the retina.[1]

In addition to the foregoing considerations, the prismatic action of lenses is an important factor in the correction of anisometropia. This action is a not uncommon cause of confusion in isometropia, and much more so must it be when, as in anisometropia, the prismatic deviation does not correspond in the two eyes.

All these difficulties apply to anisometropes who have been accustomed to binocular vision without lenses; it is far more difficult to institute binocular vision in those who have, perhaps long ago, contracted the habit of excluding one eye. In the vast majority of such cases it is impossible (except at an early age) to secure binocular vision, and especially is this true when one eye is used for distant and one for near vision.

When anisometropia results from removal of cataract from one eye while the other eye has good vision, the aphakic eye may be of great service in extending the field of vision and even in entering subordinately into binocular vision; but very rarely will such an eye accept correction by a strong convex lens. This is at least partly due to the difficulty of avoiding diplopia which tends to result from the one-sided prismatic deviation.

The student will already have concluded that the treatment of anisometropia is attended with much difficulty and uncertainty. The course to be pursued

[1] In addition to the purely psychic influence, the actual distortion of the retinal image in one eye has a decided influence upon the form of objects as seen binocularly. This complex subject has been interestingly discussed by Wadsworth (Effect of a Cylindrical Lens with Vertical Axis, Trans. Am. Ophth. Soc., 1875); by Lippincott (Binocular Metamorphopsia, Arch. of Ophth., 1889, and New Tests for Binocular Vision, Trans. Am. Ophth. Soc., 1890), and by Green (Stereoscopic Illusions Evoked by Prismatic and Cylindrical Glasses, Trans. Am. Ophth. Soc., 1889).

must in every case be adapted to the age and condition of the patient. Childhood is the most favorable age. By the correction of the refractive error of each eye in young children many eyes which would otherwise become useless are trained to perform their part in binocular vision; if strabismus and inferior visual acuteness are also present, the eye should be aided by stereoscopic or other exercises (Chapter XVII.).

In young adults having binocular vision with anisometropia, the first attempt should be to equalize the refraction, and especially if asthenopic symptoms are present which are referable to the anisometropia. If such correction is not accepted, the symptoms may perhaps be relieved by partial equalization.

It may be stated, as a general rule, that in persons who have reached the presbyopic age without equalization of refraction the correction of anisometropia (except in the lowest degrees) will not be tolerated, and this, whether the glasses are for distant or for near use.

As previously indicated, the correction of anisometropia without binocular vision in adults will almost invariably be a thankless task.

In all cases of anisometropia in which correction is attempted, the greatest care must be bestowed upon the proper adjustment of the lenses, in accordance with the instructions given in Chapter XII.

CHAPTER XVI.

PRESBYOPIA AND ANOMALIES OF ACCOMMODATION.

We have learned that the accommodative power suffers a gradual diminution with advancing years (p. 157). When the amplitude falls below 4.5 D. the emmetrope cannot read small print comfortably, since this must be held about $\frac{1}{3}$ metre (13 inches) from the eye in order that the retinal image may be of sufficient size. This requires 3 D. of accommodation, and as only two-thirds of the total amplitude can be used continuously (p. 160), fatigue will soon be experienced unless there is an amplitude of at least 4.5 D. With this amount of accommodation distinct vision is possible for a short period at a distance of 22 cm. (9 inches); hence, when distinct vision at this distance is not possible, the accommodative power is insufficient for close application of the eyes in near work. When this failure of accommodation is due to the above-mentioned cause (physiological sclerosis of the lens) the resulting condition is called *presbyopia* (old sight). Presbyopia may, therefore, be defined as that physiological condition in which from advance of age the amplitude of accommodation is less than 4.5 D.; or it is that condition in which, from advance of age, distinct vision at 22 cm. is not possible when any existing ametropia is corrected.

Age at which Presbyopia Occurs.—Reference to the table (p. 158) indicates the age of forty years as that at which the failing accommodative power reaches

the limit of amplitude compatible with close application of the eyes. Shortly after this age—almost always before the forty-fifth year—the onset of presbyopia occurs.

Symptoms.—The most characteristic symptoms are a disposition to hold the book or other work at too great a distance, asthenopia, and, in neglected cases, congestion or inflammation of the conjunctiva.

Diagnosis.—This may ordinarily be made without difficulty, in accordance with the age and the inability to read fine print. The static refraction must be first corrected in order to exclude hyperopia and astigmatism in those cases in which distinct vision is not possible at 22 cm., and to exclude myopia, in which presbyopia may readily coexist with good near vision.

It is also necessary to distinguish between insufficient accommodation resulting from the physiological sclerosis of the lens and that which is due to weakness (paresis) or paralysis of the ciliary muscle.

Jaeger's Test Type for Determining the Amplitude of Accommodation.—As Snellen's test letters have gained universal recognition for the determination of distant visual acuteness, so the test cards of Jaeger are everywhere in use for testing near vision. These cards consist of selections of reading matter printed in type of various sizes. No. 1, being the smallest, is intended to be read at 22 cm. or less. If distant vision is normal while this print cannot be read, deficiency of accommodative power for near work is demonstrated. The larger type are intended for those who from failure of accommodation or from other cause cannot read the smallest print. The nearest point at which the smallest distinguishable type can be clearly seen is the *punctum proximum* (p. p.) or near-point of the eye, and, as such, it measures the amplitude of accommodation.

Oliver's Test Letters.—While well adapted for the purpose for which they were intended, Jaeger's test type

are not based upon scientific measurements as are those of Snellen. To meet this deficiency, Oliver has constructed test letters for near vision in conformity with the minimum visual angle principle of Snellen.[1]

Treatment.—The age at which persons seek relief from presbyopia varies with the individual accommodative amplitude and with the character of the work pursued. The average may be placed at the forty-fifth year. At this age a convex spherical lens of 1 D. will probably be the correction required. Persons whose work necessitates continuous eye-strain may feel the need of assistance in near work at an earlier age—at any time after the fortieth year. In these cases a lens of 0.50 D. or 0.75 D. will usually suffice until the forty-fifth year or thereabout.

The average amount of accommodation possessed by healthy persons between the ages of forty and seventy-five years and the probable strength of lens for adapting the eye for continuous near work is indicated in the following table:

Age . .	40	45	50	55	60	65	70	75
Accom. .	4.5 D.	3.5 D.	2.5 D.	1.75 D.	1 D.	0.75 D.	0.25 D.	0.
Lens . .		1 D.	2 D.	2.75 D.	3.25 D.	3.5 D.	3.5 D.	3.5 D.

Although this table serves as a guide, it is not to be blindly followed in individual cases. The appropriate lens must be selected in each case in accordance with the amplitude of accommodation and the distance for which it is desirable that the eyes may be adapted.

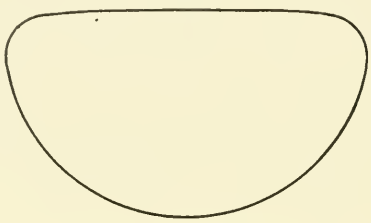
Any change of lenses which may be required after the age of sixty-five years is ordinarily due to change in the static refraction, as not infrequently occurs in old age.

It is apparent that as the strength of the presbyopic lens is increased the range of vision is diminished,

[1] It has not been thought necessary to reproduce here samples of Jaeger's or Oliver's test type. They may be obtained from any optician.

since the lenses have the effect of making the eyes myopic, greatly to the detriment of distant vision. On this account elderly people usually acquire the habit of wearing their near-glasses far down on the nose, so that they may look above them during distant vision. A convenient form of glass, sometimes

FIG. 76.



preferred by business men and public speakers is that known as the clerical lens (Fig. 76), which has the upper portion cut away.

Bifocal Lenses.—Ametropes who require glasses for distance and other glasses for near use sometimes find

FIG. 77.

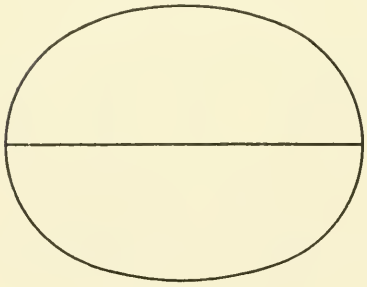
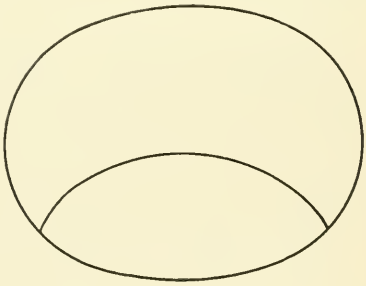


FIG. 78.



great comfort in bifocal glasses, although some persons reject them because of the restricted field of view. The original split bifocal or *Franklin lenses* consist of two lenses, each properly centred, and separated by a horizontal line (Fig. 77). The upper lens is for distant and the lower lens for near vision. Because of

the too restricted field of view for distance, Franklin's invention has been modified by making the dividing line crescentic (Fig. 78). There are several ways of making such glasses. The most common method consists in cementing the appropriate presbyopic correction to the lower part of the distance glass; but the distance and near lenses may be separate as in the Franklin lenses, the dividing line being crescentic (Morek's perfection bifocals). It is possible also to grind the two lenses upon a single piece of glass, thus avoiding the dividing line, which is somewhat clumsy in appearance ; but glasses of this kind are expensive and not usually satisfactory.[1] Finally, achromatic or *invisible* bifocals are sometimes made. They consist of the proper distance correction, made of crown glass, in the lower segment of which a concavity is ground, and in this concavity a convex lens of flint glass is placed, the greater index of which serves for the near correction. These glasses present a very neat appearance, but their high price precludes their general use. They are particularly desirable, on account of their achromatic effect, in aphakia.

SPASM OF ACCOMMODATION.

Owing to the extreme ease of accommodative changes in childhood, there is in almost all young hyperopes a diminution of the hyperopia effected by action of the ciliary muscle ; so accustomed is the young hyperope to exercise this accommodation that he will be unable totally to relax it when the correcting lens is placed before his eye. A certain amount of unrelaxable

[1] This is partly because of the prismatic effect, which cannot be avoided, and partly because in convex lenses the segment must be inverted. This form, however, may occasionally be used with cosmetic advantage in lorgnettes.

accommodation is physiological, being due to the tone of the ciliary muscle. The condition of muscular rest is not that of complete relaxation as in paralysis: the tone of the muscle keeps it in a state of slight contraction. Hence, even in adults the refractive power of an eye is slightly less when tested under cycloplegia than it is when the eye is in its normal condition. The increase of refraction arising from physiological tone of the ciliary muscle may vary from 0.25 D. to 0.50 D. in the adult to 1 D. or more in childhood.

Not infrequently in childhood and early adult life the action of the extremely excitable ciliary muscle transcends the physiological limit, giving rise to the condition of cramp or *spasm of accommodation*. In this state an existing hyperopia may be overcorrected, producing an apparent myopia.

The effort to overcome hyperopia is not, however, the only cause of accommodative spasm. This may be attributed to astigmatism, myopia (thus increasing the degree), overuse of the eyes, insufficiency of convergence, hysteria, and to irritation from the local application of certain drugs (miotics), such as eserin and pilocarpin.

Symptoms.—The symptoms which, when taken in conjunction with the age (childhood and early adult life), are characteristic of accommodative spasm are inability to see clearly at a distance (if the spasmodic action overcorrects any existing hyperopia), asthenopia, headache, macropsia, and monocular polyopia.

Macropsia.—In accommodative spasm a very slight impulse produces an inordinately great accommodative action, and in order to adapt the eye for a certain distance, a much slighter innervation of the accommodative centre is requisite than under normal conditions. Because of this unnaturally slight effort of accommodation, objects are supposed to be farther away and consequently larger than they really are (p. 238).

Since the size of objects is judged in accordance with previous experience, this symptom occurs only in recently acquired spasm, such as is occasionally manifested in hysteria (hysterical amblyopia), or as is produced by the instillation of a miotic.

Monocular Polyopia.—This has already been mentioned (p. 284) as occurring in ametropia; the same explanation serves to explain that which occurs in accommodative spasm, since in this condition the eye is rendered myopic by the excessive action of the accommodation.

Diagnosis.—The diagnosis is made in accordance with the above-mentioned characteristics, corroborated by determination of the true refractive condition with the aid of atropin-cycloplegia. In order to ensure relaxation in accommodative spasm the atropin solution (1 per cent.) should be used four times a day for several days, or for a week in obstinate cases.

The diagnosis of the cause of the spasmodic action is not always easily made. If the spasm is not due to refractive error, which is by far the most common cause, hysteria, cerebral lesion, or other irritative affection may be suspected, according to circumstances.

Treatment.—This consists in removal of the cause, if possible. Any refractive error which may be present must be corrected, and in order that the eyes may adapt themselves to the glasses it may be necessary to continue the application of atropin for several weeks or longer.

PARESIS AND PARALYSIS OF ACCOMMODATION.

Weakness of accommodation is a common accompaniment of the general physical debility following severe constitutional diseases; but in addition to this enfeeblement, there is also exerted by certain affections

a direct detrimental action upon the nerves of accommodation.

Diphtheritic Paralysis.—This may consist in diminution (paresis), or in complete abolition (paralysis) of the accommodative function. In such cases the diphtheritic toxin produces a peripheral ciliary neuritis; the inflammation also frequently affects other branches of the third nerve, causing ptosis and divergent strabismus. Diphtheritic paralysis is not confined to the third nerve; the palatal muscles are also frequently affected. Paralytic symptoms occur after subsidence of the febrile stage, usually in the second or third week of convalescence. Complete recovery follows usually in about a month.

Syphilitic Paralysis.—This results from injury to the nerves or their centres by gummatous deposit. Accommodation may be paralyzed without involvement of the iris, or there may be both cycloplegia and mydriasis (*internal ophthalmoplegia*), with or without paralysis of the external ocular muscles. Disease of the ciliary ganglion may give rise to unilateral cycloplegia.

Paralysis Caused by Non-syphilitic Brain Lesion.—Paresis or complete paralysis of accommodation may also result from alcohol or tobacco poisoning, from meningitis, brain tumor, tabes, or other cerebral affection. Here, as in syphilitic nuclear disease, there may be cycloplegia with or without mydriasis, and with or without involvement of the extra-ocular muscles.

Glaucomatous Paralysis.—The abnormally great pressure upon the ciliary nerves in glaucoma produces a paralytic state of these nerves, with a consequent deterioration of accommodative function.

Accommodative Paralysis Arising from Other Diseases.—Diabetes, rheumatism, gout, lithiasis, and various other diseases and severe contusions sometimes

exert a direct action upon the accommodative apparatus, causing an abridgment or abolition of function.

Artificial Cycloplegia.—We have already learned that the instillation into the conjunctival sac (or the internal administration of large doses) of atropin and similar drugs produces paralysis of accommodation and mydriasis (Chapter XI.).

Symptoms and Diagnosis of Accommodative Paralysis.—The most characteristic symptom is inability to see near objects clearly (except in myopia). As macropsia occurs in spasm of accommodation, so micropsia is a not uncommon manifestation of cycloplegia. The attendant mydriasis may give rise to dazzling, dizziness, and nausea.

The diagnosis is made by ascertaining the amplitude of accommodation and excluding presbyopia. The amplitude may be determined with Jaeger's test type and, if the pupil is moderately dilated, by skiascopy. If, after the static refraction has been ascertained, the person under examination is directed to look at an object placed near the punctum proximum of convergence, the examiner may decide in accordance with the principles of skiascopy whether the eye becomes myopic through exercise of accommodation, and, if so, to what extent.

Treatment of Accommodative Paralysis.—The treatment depends upon the cause of the paralysis, which must be determined, if possible. Hygienic and tonic treatment for the debilitated, mercury and iodides for syphilis are evident indications. In chronic non-syphilitic brain lesions not much can be done. If mydriasis coexists, and especially in artificial cycloplegia, dazzling must be prevented by the use of dark glasses.

Loss of Accommodation from Absence or Luxation of the Lens.—Accommodation is clearly impossible when the crystalline lens is absent from the

eye, for the most energetic contraction of the ciliary muscle does not increase the curvature of the cornea to a degree capable of measurement with the keratometer. The apparent accommodation which sometimes occurs in such eyes is due to contraction of the pupil and to unusual ability to interpret diffusion-images.

In luxation of the lens the condition resembles aphakia if the lens does not lie in the pupillary space; but when, in partial luxation, the lens retains its position in the pupil, it assumes its accommodation-curvature, which cannot be overcome.

PART IV.

DISORDERS OF MOTILITY.

CHAPTER XVII.

NON-PARALYTIC DISORDERS OF MUSCULAR EQUILIBRIUM.

Deviation from perfect muscular adjustment (orthophoria) may be due to a number of causes. These may be divided into two general classes—*non-paralytic* and *paralytic*. Only the disorders arising from the former of these classes are to be included in the present chapter, and it should be so understood without further allusion.

EXCESS OF CONVERGENCE.

We have learned (p. 171) that binocular vision is often maintained even though the muscular balance may differ considerably from the orthophoric standard. Since in this case the proper convergence of the visual lines is preserved, the condition is characterized as *latent* strabismus. If the tendency is toward excessive convergence, the condition may be conveniently expressed by the term *esophoria* (Stevens).

When the esophoric tendency is very strong a great and continued strain is imposed upon the nerve centres

in order to supply sufficient innervation to the divergence muscles for the counterbalancing of the overactive convergence. Beyond a certain period this effort cannot be continued, and vision is then performed with one eye while the other is allowed to seek its position of equilibrium. This constitutes *manifest* excess of convergence or *convergent strabismus* (convergent squint), or *esotropia* (Stevens).

Latent excess of convergence may, therefore, be converted into manifest strabismus at certain times, as when the eyes are tired from prolonged use, and especially in near vision, when spasm of convergence is frequently incited through association of accommodation. In such cases the strabismus is said to be *intermittent.*

But when the effort necessary for binocular vision is very great or when the fusion-impulse is weak, it usually happens that the child (convergent strabismus almost always develops in childhood), having once learned the art of squinting with monocular vision, will altogether abandon the effort to maintain proper convergence; the strabismus thus becomes *constant* or *permanent.*

If vision is equally good in the two eyes, either eye may be used for fixation while the other squints; this is *alternate* strabismus. But, as a rule, in strabismus one eye will be preferred to the other, and fixation will be performed always with the better eye, while the inferior eye falls into a state of permanent deviation. Although thus apparently confined to one eye, this kind of strabismus is not a monocular affection: the excessive convergence is effected by innervation of both internal recti; but in order that the visual line of the fixing eye may be properly directed, adduction of this eye is prevented by suitable innervation of its external rectus, just as when convergence is maintained together with a lateral deviation of the two eyes

(Landolt). In strabismus this is usually effected by turning the head to one side.

Although the convergence is always in excess of the appropriate amount, it diminishes or increases with the recession or approach of the object of fixation; moreover, the convergence-excess remains undisturbed throughout the field of fixation, for the two eyes move together in all directions. In this respect non-paralytic differs from paralytic strabismus, and because of this freedom of movement the former is called *concomitant* strabismus.

In recently formed concomitant strabismus there is no abnormal limitation of the field of fixation in any direction, but when from long-continued overaction the internal recti have become permanently shortened while the external recti have become correspondingly weakened, the power of abduction (external rotation) falls appreciably below that of the normal eye; and since the internal rectus of the deviating eye is the muscle which undergoes the greater shortening, the external rotation of this eye is not infrequently less extensive than that of the other eye.

Etiology of Excess of Convergence.

We have learned (p. 170) that through the variation in the relative accommodation and convergence distinct binocular vision is possible in ametropia. This may occur in two ways: (1) The relation between accommodation and convergence may be so modified by long association that orthophoria coexists with ametropia or (2) the orthophoric condition may not be attained, but whatever imbalance remains may be latent. In hyperopia the tendency is toward excessive convergence, since the inordinately great accommodative effort required for distinctness of images provokes a greater convergence impulse than

the distance of the object demands. This convergence excess may be latent, as above stated, thus permitting binocular vision, or it may be manifested as convergent strabismus. Hyperopia is, therefore, a common contributing cause of excessive convergence.

In childhood convergence is especially easy, owing to the smallness of the eyes and the shortness of the interocular distance. Because of this facility for convergence and of the irritation transmitted from the accommodation centre, the internal recti are thrown into a spasmodic condition in convergent strabismus, thus increasing the degree of strabismus and effecting its continuance even when accommodation is completely relaxed. This spasm of convergence gradually gives place to anatomical shortening of the internal recti muscles, and especially of the internal rectus of the deviating eye.

Spasm of convergence has also been attributed to a number of other causes (corneal inflammations, etc.), but for the most part without sufficient reason. It may, however, be due to hysteria or to other nervous hypersensitiveness.

The relative strength and position of scleral attachment of the internal as compared with the external recti muscles must also be regarded as a factor in determining the predominance of convergence over divergence.

Defective development of the cerebral fusion centres is, doubtless, an important factor in the etiology of convergent strabismus.[1] In certain cases of intractable alternate strabismus with normal visual acuity in each eye it is not unreasonable to assume a congenital absence of the fusion faculty, but in a much larger proportion of cases there are other factors to be considered

[1] Worth, Etiology and Treatment of Convergent Strabismus, Lancet, May 11, 1901, p. 1323.

which militate against the post-natal development of this innate faculty. The principal of these contributing causes have been mentioned in the chapter on Hyperopia.

Symptoms of Excess of Convergence.

Slight esophoria may, as has already been mentioned, cause no disturbance whatever. The least amount which is capable of giving rise to asthenopia cannot be definitely stated, since this must vary with the resisting power of the nervous system; but in general, it may be said, an amount not exceeding 2^{Δ} or 3^{Δ} (at 6 metres) must be placed within the limits of normal muscular equilibrium.[1]

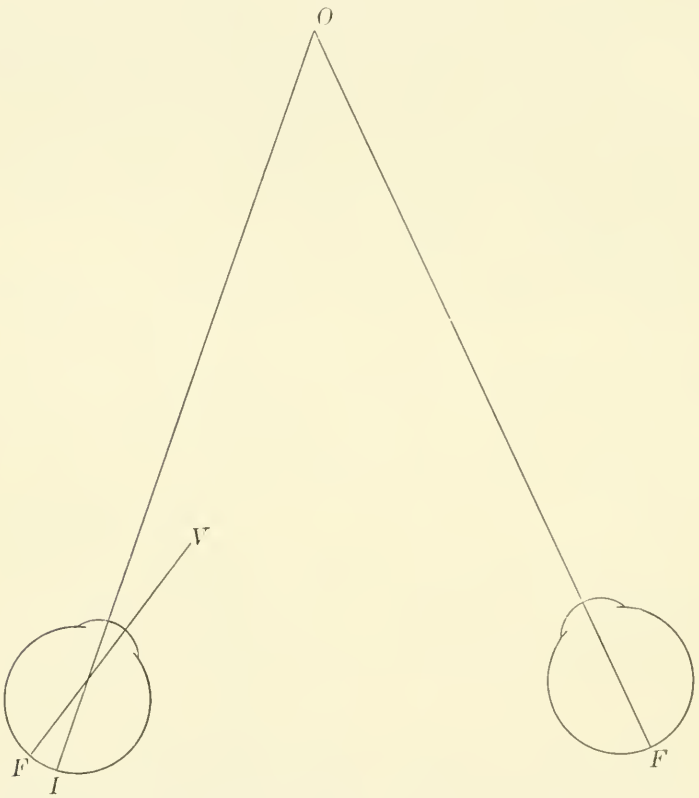
When the tendency to convergence is so great that the proper directions of the visual lines cannot be maintained—that is, when esophoria passes into esotropia or convergent strabismus—muscular asthenopia is replaced by a new train of symptoms which originate from the loss of binocular single vision.

Diplopia.—We know that distinct vision is possible only when the image falls upon the fovea, and that the mental fusion into a single perception of the two retinal images is possible only when the image falls upon the fovea of each eye. When the proper convergence is not maintained one eye (*the fixing eye*) will be so directed as to receive the image upon its fovea, while the other eye must receive the image upon an eccentric part of its retina, and at the same time some other external object will cast its image upon the fovea of this eye. Under experimental conditions the mind can form a fused perception of the two images cast upon the two foveas, as when a part of a familiar

[1] In fact, many authorities (Standish, Posey, and others) believe that the normal muscular balance is that of esophoria of 2° or 3° at 6 m. with a corresponding exophoria of 2° or 3° at the reading distance (25 cm.).

picture is made with a stereoscope to fall upon the fovea of one eye and the complement of this picture is made to fall upon the fovea of the other eye. Thus, the image of a horse being presented to one eye and that of a man in the attitude of rider to the other eye, the mental picture of the rider upon the horse may

FIG. 79.



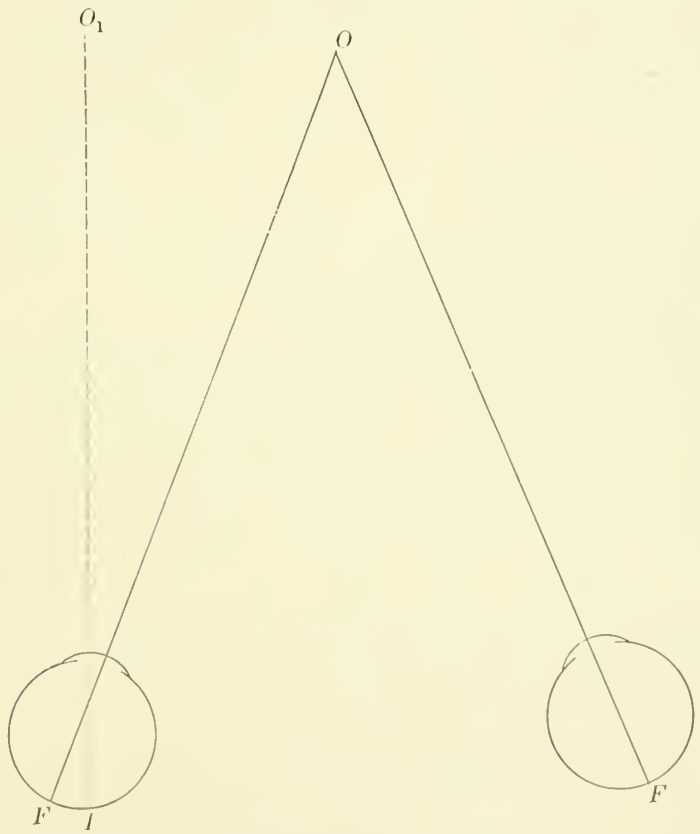
Illustrating the position on the retina of the false image (*I*) in strabismus.

be perceived. But under ordinary conditions the mind will be concentrated upon one object (*the object of fixation*), and a distinct mental impression (*the true image*) will be conveyed through the fixing eye, which receives the image upon its fovea, while a less defined impression (*the false image*) will be conveyed through

the deviating eye, which receives the image upon an eccentric part of its retina. This constitutes *binocular double vision* or *binocular diplopia.*

Orientation of the False Image.—In convergent strabismus the deviating eye receives the image of the

FIG. 80.



Illustrating the direction of projection ($I\,O_1$) of the false image (I) in strabismus.

object of fixation upon a part of the retina which is situated on the nasal side of the fovea (Fig. 79). In normal vision this part of the retina could be stimulated only by an object situated on the temporal side of the object of fixation (Fig. 80). The subject of

strabismus, not being able to readjust the nerve associations, assigns such position to the object of vision as an object stimulating the *same* part of the retina would have if perceived through an eye in its normal position. Hence, in convergent strabismus, the nasal side of the retina being stimulated in the deviating eye, the false image is displaced to the temporal side; that is, to the right side if the right eye deviates inward, and to the left side if the left eye deviates inward. The true image being seen in its correct position, the false image appears (relatively to the true image) to lie on the side corresponding to the deviating eye. This is called *homonymous* diplopia in contradistinction to *crossed diplopia*, which occurs in divergent strabismus.

Diplopia in Esophoria.—As long as the tendency to excessive convergence is latent, diplopia does not occur; but it is impossible to assign a line of demarcation between esophoria and esotropia. In the higher degrees of what is usually classed as esophoria the most distressing symptoms are due to unconscious diplopia, which occurs when the eyes are tired from prolonged use or when the bodily vigor is reduced. When this diplopia has been demonstrated by suitable tests the patient may realize that he has periodically suffered from diplopia without being aware of the nature of his trouble.

Diplopia in Convergent Strabismus.—In permanent non-paralytic convergent strabismus diplopia is not a common symptom because of the early age at which this kind of strabismus develops. Diplopia may be demonstrated in some cases of long continuance, but more frequently that part of the retina upon which the false image falls is not capable of transmitting stimulation to the centres of consciousness. This is the result of the cultivated power of disregarding the false image. That part of the retina which has ac-

quired this insensitiveness is called the *region of exclusion*. That the entire retina does not possess this property is demonstrated by placing a prism before the deviating eye, thus throwing the false image upon an unaccustomed region of the retina, when diplopia will occur.

In certain cases there appears to have developed a new association of nerve fibres whereby the false image is fused with the true image, the former being assigned its correct position in space. In these cases a temporary diplopia occurs after a successful operation for the strabismic defect.

Amblyopia ex Anopsia.—The visual acuity of the deviating eye is much reduced in all long-standing cases of permanent non-paralytic convergent strabismus. In most of these cases the vision of the squinting eye was doubtless defective prior to the occurrence of strabismus, the defective vision being the determining cause of the strabismus; but abundant observation has shown that squinting eyes which possessed good visual power in early life have so far deteriorated after long-continued disuse as even to lose the power of fixation.

Notwithstanding the inferiority of vision of the squinting eye, this eye is still of material assistance in extending the field of vision. It is significant also that the extreme inner part of the retina, corresponding to the temporal field on the affected side, does not suffer the deterioration which involves the macular region.

Deviation of the Non-fixing Eye.—The inward deviation of the cornea of the non-fixing eye is the characteristic objective symptom of convergent strabismus. This deviation may be so slight as to be unnoticeable on casual observation, or it may be so great that a portion of the cornea is hidden behind the inner angle of the lids, thus producing very great disfigurement.

Diagnosis of Excess of Convergence.

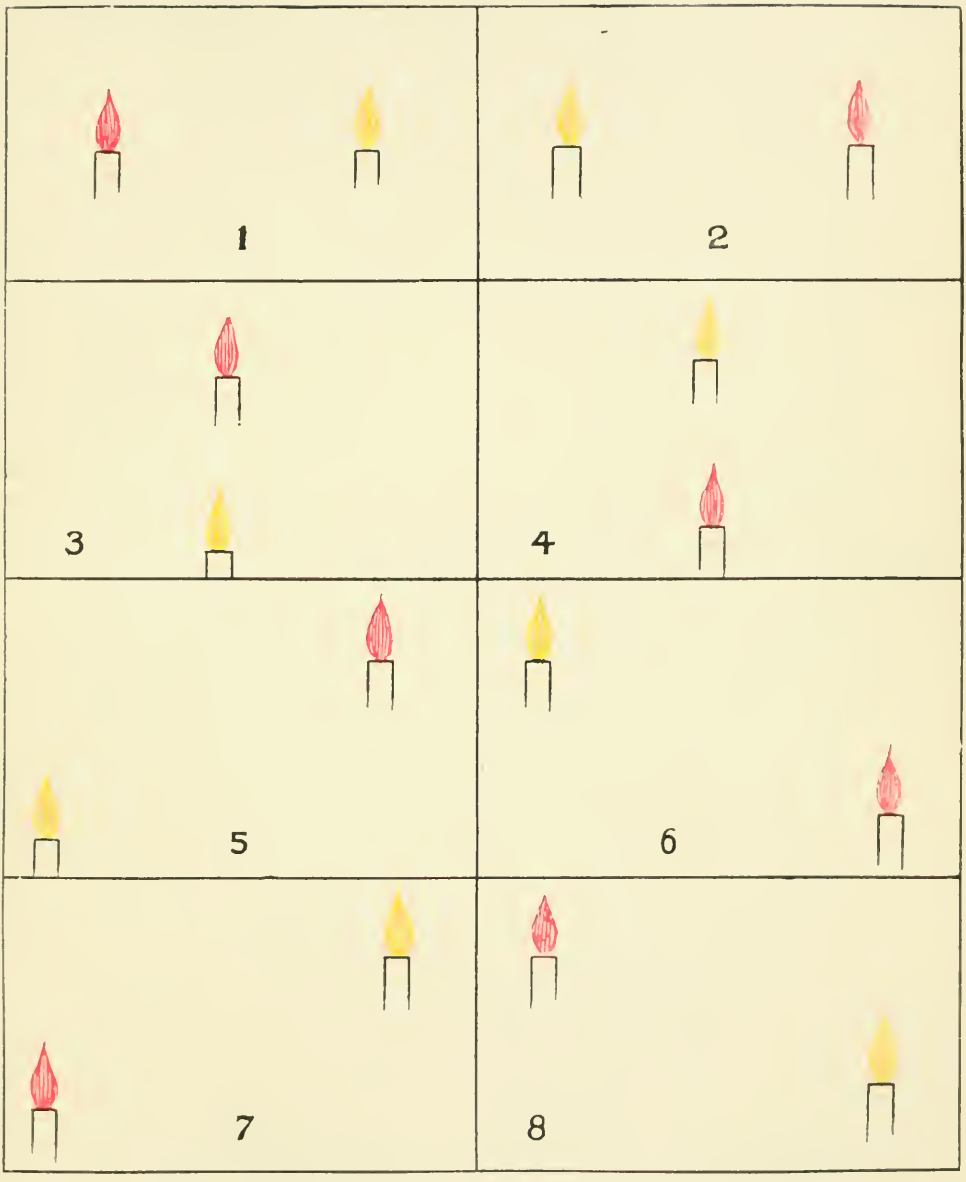
Cover Test.—The simplest method of determining excess of convergence is that of covering one eye while the other eye is directed toward some point of fixation. If orthophoria exists the covered eye maintains the proper direction for fixation; but if convergence is relatively in excess of accommodation, the covered eye deviates inward. If the excess of convergence is latent (esophoria) the eye resumes its proper direction at the moment when it is uncovered (*movement of redress*). Hence, the examiner watches to see if the eye makes the movement of redress when it is uncovered.

If, in convergent strabismus, vision is performed monocularly, but equally well with either eye, the movement of redress will not occur, but the deviation may be demonstrated by covering first one eye and then the other; when the fixing eye is covered, the other moves into position for fixation.

In long-standing convergent strabismus the unused eye may not be able to perform fixation, such vision as remains being eccentric; but in these cases the diagnosis is apparent from superficial observation.

Red Glass Test.—When a red glass is placed before one eye the impulse for binocular vision is materially reduced, and in heterophoria two images of a flame, one of them red and the other yellowish, may be seen. The relative position of the double images serves to indicate the kind and degree of heterophoria. (Plate IV.) The prism which causes the two images to be fused is the measure of the muscular error. This test is not as accurate as some others, because when the images are brought into fairly close approximation fusion is completed by muscular effort; it is a convenient test, however, for demonstrating the coexistence of lateral and vertical imbalance (hyper-

PLATE IV.



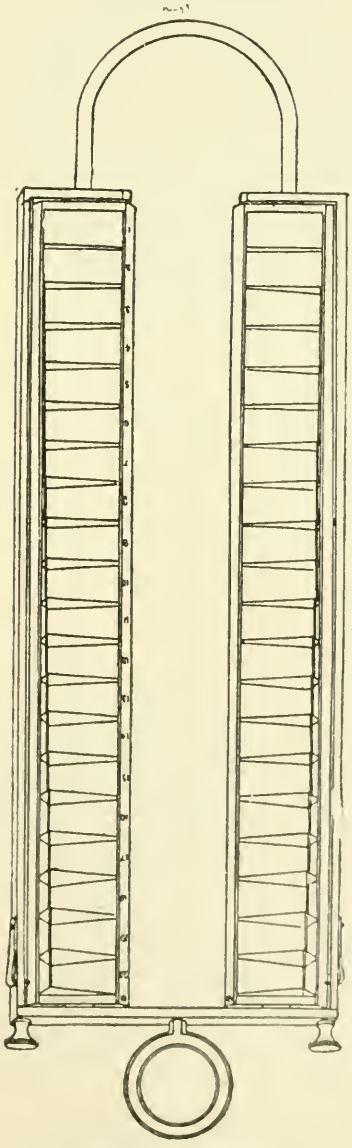
Red Glass over Right Eye.

1. Exophoria.
2. Esophoria.
3. Left Hyperphoria.
4. Right Hyperphoria.
5. Left Hyperesophoria.
6. Right Hyperesophoria.
7. Right Hyperexophoria.
8. Left Hyperexophoria.

(Colburn.)

esophoria and hyper-exophoria. The prisms required for estimating the degree of heterophoria may be taken from the trial case and placed in the trial frame, or, as

FIG. 81.



Gould's prism battery.

is more convenient, a series of prisms of gradually increasing strength may be arranged in a suitable support and held by the examiner so that any desired prism may be quickly brought before the eye (Fig. 81).

Graefe's Diplopia Test.—This consists in the production of vertical diplopia by placing a prism, having its base up or down, before one eye. Since binocular single vision is not possible under these conditions (if the strength of the prism exceeds 3 or 4), the eyes assume their position of equilibrium. To ascertain this position in distant vision, a candle flame or other suitable light is placed at a distance of 6 metres or more, while the patient, having a prism of 8 , base up (or down), before one eye, looks at the flame and notes whether one of the two images is directly above the other or displaced to one side. In the former case, there being no lateral displacement, orthophoria (as regards lateral action) is present. If the image corresponding to the eye which has the prism before it is displaced to the temporal side of this eye, there is homonymous diplopia, indicating excessive convergence; if the displacement is toward the opposite side, there is crossed diplopia, indicating deficient convergence. In order to assist in assigning each image to its proper eye, a red glass may be placed before one eye, thus coloring the image which corresponds to this eye.

That prism which annuls the lateral displacement, making one image lie vertically over the other, measures the degree of lateral heterophoria. In esophoria the base of the prism must be placed *out* (toward the temple), while in exophoria the base must be placed *in* (toward the nose). The required prism may be taken from the trial case, from the prism battery (Fig. 81), or from a rotary prism. *Risley's rotary prism* (Fig. 82) consists of two superimposed prisms,

with a device for rotating their bases in opposite directions, by which means the effect of a single varying

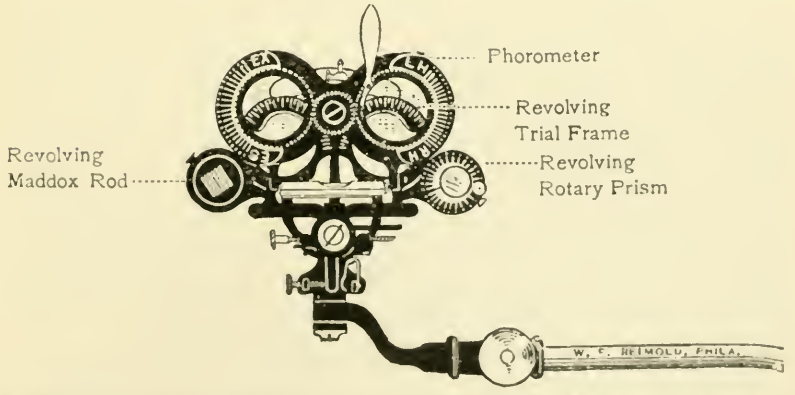
Fig. 82.

Risley's rotary prism.

prism results, the strength of this prism being indicated on a scale. This prism is intended to be placed in the trial frame.

Stevens' phorometer (Fig. 83) consists of a pair of prisms, each of 5△, suitably mounted upon a bracket

Fig. 83.



Stevens' phorometer, Risley's rotary prism, Maddox rod, and frame for trial lenses combined in a single instrument

or stand, and so arranged that the rotation of one prism is conveyed to the other. By this means when

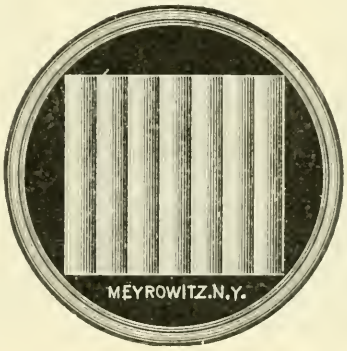
the base of one prism is directly *up* (toward the brow) the base of the other is directly *down;* when the base apex line of one prism is horizontal that of the other is likewise horizontal, both bases being *in* (toward the nose) or both being *out* (toward the temples). This instrument is very convenient for the application of Graefe's test. In testing the lateral muscles vertical diplopia is produced by placing the base of one prism up and that of the other prism down. If the double images do not appear in a vertical line, there is esophoria or exophoria. By rotating the prisms the images are shifted so that one lies directly over the other, the degree of imbalance being indicated on a scale in accordance with the amount of rotation required. In testing the vertically acting muscles the prisms are rotated into the horizontal plane for the production of lateral diplopia, when any existing hyperphoria will be manifested by one of the double images being higher than the other. The degree of imbalance can be ascertained by rotation of the prisms until the two images lie in the same horizontal plane.

The relation between convergence and accommodation at the reading distance is determined with the aid of a black dot on white paper. A vertical line drawn through the dot may be of assistance in determining the relative position of the images. The vertically displacing prism being placed before one eye, lateral orthophoria exists if one image of the dot is vertically over the other; but if this is not so, the condition is that of esophoria or exophoria, according as there is homonymous or crossed displacement of images. This test may also be made with the phorometer.

Maddox Rod Test.—The Maddox rod consists of a small glass cylinder, or a series of parallel cylinders (Fig. 84), mounted in an opaque diaphragm of suitable size to be placed in a trial frame. The cylinder produces very great magnification of images in the direc-

tion at right angles to its axis; a small flame as seen through this cylinder appears as a long streak of light. Hence, if the cylinder is placed, with its axis horizontal, before one eye while a small light is viewed binocularly, the vertical streak, as seen with one eye, cannot be fused with the flame as seen with the other eye, and in the abandonment of the attempt to effect fusion the eyes assume their position of equilibrium. If the streak of light appears to pass vertically through the flame, there is no disorder of convergence; if the

FIG. 84.

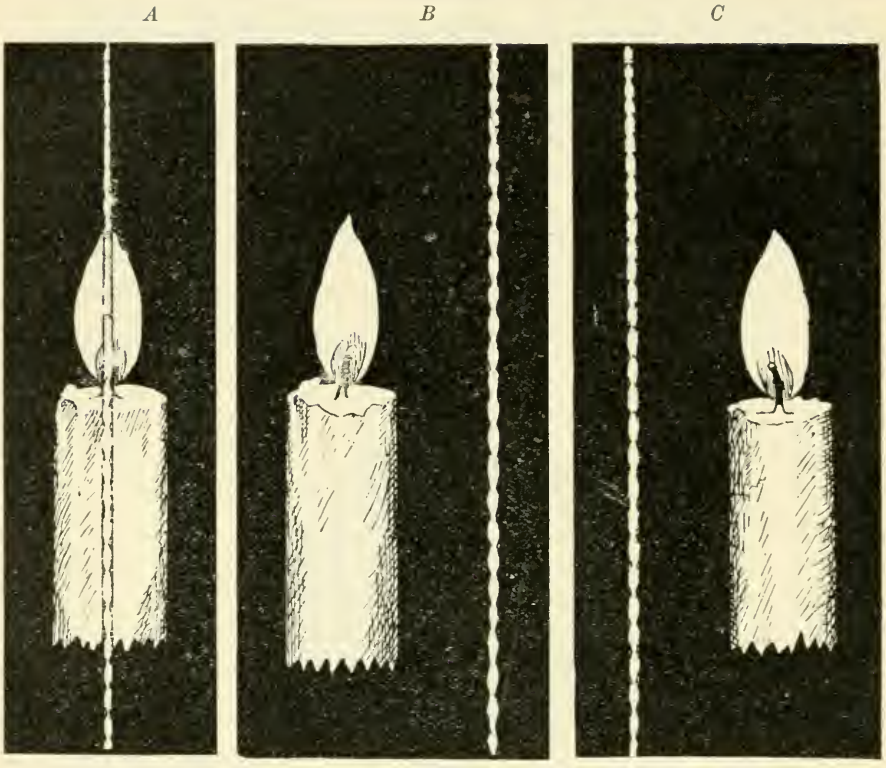


Maddox multiple rod.

streak is displaced homonymously, there is esophoria, and if there is crossed displacement the condition is that of exophoria (Fig. 85). The prism which causes the streak to pass vertically through the flame measures the lateral heterophoria.

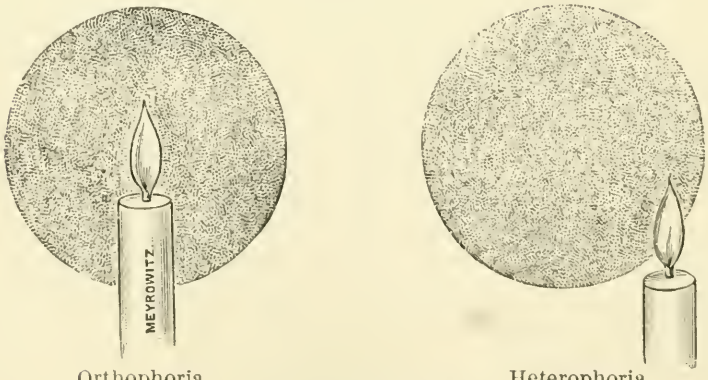
The Stenopæic Lens Test (Stevens). —A strong convex lens (13 D.) is covered by an opaque disk having a small, circular opening at its centre. If one looks through this aperture, a distant flame appears as a circular blur of light (Fig. 86). If the muscles are normally balanced, the flame, as seen by the fellow-eye (this being uncovered), will appear to be at the centre of the blurred image. In heterophoria the clear image

FIG. 85.



Maddox rod test for horizontal deviation ; the rod is before the right eye. *A*. The line passes through the flame—orthophoria. *B*. The line passes to right of the flame—esophoria. *C*. The line passes to left of the flame—exophoria. (de Schweinitz and Randall.)

FIG 86.



Orthophoria. Heterophoria.

The stenopæic lens test.

will not lie at the centre of the field, but will be displaced in accordance with the kind and degree of muscular error, which is measured by the prism required to bring the image of the flame into the centre of the field.

Significance of the Tests for Heterophoria.— It should be noted that each of these tests determines only the position of muscular equilibrium in the absence of stimulation of the centres for convergence and divergence, except such stimulation as is conveyed through the association of accommodation.

It might seem, therefore, as if the results thus obtained would be of no great value in revealing the adaptability of the ocular muscles during physiological stimulation conveyed by the impulse for avoidance of diplopia. Accordingly, too much importance should not be attached to slight heterophoria as determined by these tests; but, on the other hand, so intimate is the association between convergence and accommodation that any very marked deviation from orthophoria almost invariably indicates that an excessive nervous strain is required for the performance of binocular single vision.

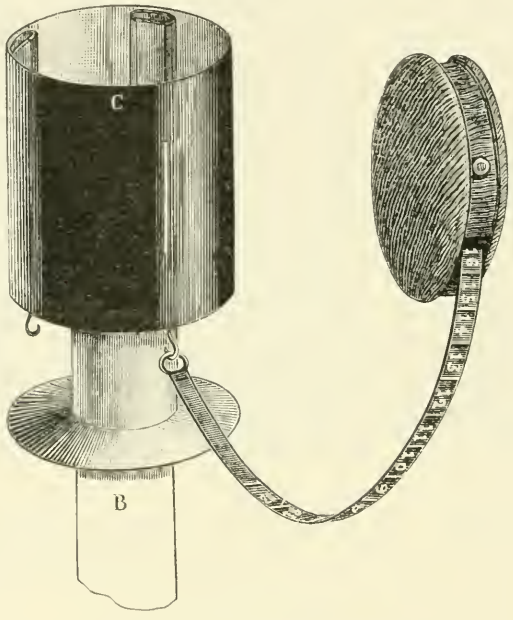
Measurement of Convergence and Divergence.— Convergence is most conveniently measured with Landolt's ophthalmo-dynamometer (Fig. 87). This consists of a candle, an opaque shade, in which a vertical slit is cut, and a tape measure, graduated in centimetres and in metre-angles.[1] The candle being lighted, the person undergoing examination looks at the slit while this is made gradually to approach his eyes; when the slit appears double (crossed diplopia), the limit of convergence has been passed. The normal amplitude is from 9 ma. to 10 ma., but an amount in excess of this would

[1] This instrument may be replaced by the diaphragm chimney (Fig. 62) with the opening reduced to its minimum size.

indicate improper muscular balance only when accompanied by deficient divergence.[1]

Divergence is measured by placing a prism, *base in*, before one eye (or before each eye), so that light from any point of fixation can reach both foveas only when the visual lines are divergent. Hence the strongest prism with which single vision can be maintained is the

FIG. 87.



Landolt's ophthalmo-dynamometer.

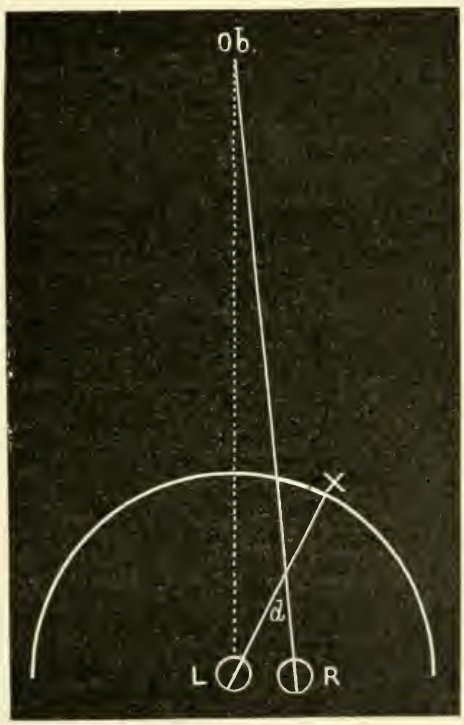
measure of the divergence. In normal muscular balance it is possible (at least after some practice) to see binocularly with a prism of 3.5° before each eye, corresponding to an amplitude of 1 ma. of divergence.

[1] Measurement of convergence may replace the less rational measurement of *adduction* (ambiguously so called). The latter is measured by the strongest prism, base out, with which a small light at a distance of 6 metres can be seen without binocular diplopia (p. 170). Adduction properly refers to the inward rotation of the eye, whether in convergence or in conjugate movement (p. 163).

Failure to reach this limit indicates deficiency of divergence.

Estimation of the Degree of Convergent Strabismus.—The prismatic method of measurement is rarely applicable in permanent convergent strabismus, owing to the difficulty of producing diplopia and to the uncertainty of orientation of the false image when this can

FIG. 88.



Measurement of squint with a perimeter. (Landolt.)

be made to appear. In these cases the angular deviation of the cornea is taken as the measure of the strabismus. This deviation may be conveniently measured with the perimeter. For this purpose the squinting eye is placed at the centre of the perimetric arc, while the fixing eye is directed toward a distant point (Fig.

88). The examiner then moves a small candle flame along the arc, until he, being directly behind the flame, sees the image of this flame (reflected from the cornea) in the middle of the pupil of the squinting eye. The number of degrees on the perimetric arc corresponding to the position of the flame measures the angular deviation, if we assume that the visual line passes through the centre of the pupil.[1]

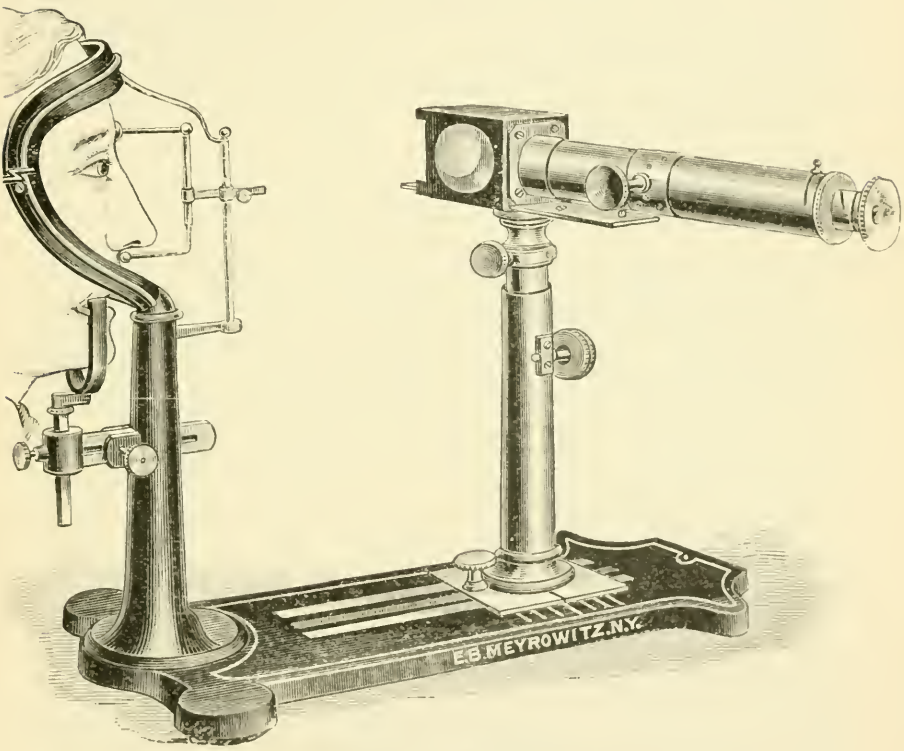
The amount of horizontal strabismus may also be roughly measured by the linear displacement of the cornea as measured along the border of the lower lid. If the squinting eye is capable of fixation, the patient is directed to look at a distant object with the better eye, while the point where the vertical line passing through the centre of the pupil cuts the lower lid is marked in ink. The better eye is then covered and the deviating eye moves into position for fixation. The point where the vertical line through the centre of the pupil cuts the lower lid is again marked, and the distance between

[1] It must be remembered, however, that this measurement determines not the real, but the apparent strabismus, which may be greater or less than the true angular deviation of the visual line. When the squinting eye is incapable of fixation it is of no importance to differentiate between the true and the apparent strabismus; when, on the other hand, this eye is capable of fixation, the same method (slightly modified) may be used to differentiate the true from the false strabismus. For this purpose the fellow eye is covered while the eye under examination is directed to the central point of the perimetric arc. The examiner then, as before, moves the candle along the arc and notes the angular marking at which he sees the flame in the middle of the pupil. This marking represents the angle which the visual line makes with the line drawn through the corneal summit and the centre of the pupil. If we regard this line (as we may do with minor error) as representing the optic axis, the record, as thus obtained, represents the angle *gamma* or *alpha* (p. 143), which two angles may, practically, be regarded as identical.

The reader will notice three separate units have been used in the measurement of convergence-anomalies: the prism-dioptre, the metre-angle, and the degree. Unfortunately no one of these units may satisfactorily displace the other two for all purposes; but no serious inconvenience need arise from the use of all three units, it only being necessary to remember that for practical purposes a prism-dioptre represents a deviation of one-half of a degree, or one-seventh of a metre-angle (p. 167).

the points measures the displacement. In an eyeball of normal size each millimetre of displacement represents about 5 degrees of deviation. If the squinting eye is not capable of fixation, the displacement is measured by comparing the horizontal distance of the pupillary centre from the canthus with the corresponding distance in the fixing eye.

FIG. 89.



Stevens' tropometer.

Measurement of the Field of Fixation.—Before deciding as to the method to be adopted in operative treatment it is advisable to ascertain the field of fixation of both eyes. This may be done with Stevens' tropometer (Fig. 89), which consists of a reflecting telescope so arranged as to enable the examiner to observe and

measure the excursions of the cornea of the eye under examination. The field of fixation may also be satisfactorily measured with the perimeter and a candle flame in a dark room. For this purpose the eye to be examined is placed at the centre of the arc and the light is moved along the arc while the eye follows as far as possible. When the limit of rotation has been passed, the examiner will no longer see the image of the flame in the middle of the pupil. If fixation cannot be performed with the squinting eye, the field of lateral excursion is determined from the extent to which this eye follows the other eye in conjugate movements, the candle flame being used as above described.

Treatment of Excess of Convergence.

The treatment of esophoria and convergent strabismus, in so far as this consists in the correction of any causative refractive error, has been considered in previous chapters. When this correction, together with hygienic, tonic, or other treatment indicated by the systemic condition, fails to afford relief, other methods must be adopted.

Prismatic Glasses.—A prism, *base out*, before each eye, enables the eyes to retain binocular single vision, while the visual lines assume the excessive convergence which is evoked by the muscular balance. In this way diplopia and its alternative, excessive nervous strain to maintain proper convergence, are both avoided, and consequently subjective disturbance may be thus relieved. But this method has its limitations, for, on account of the distorting property of prisms, it is not possible to wear strong glasses of this kind, 4 for each eye being the limit usually assigned. The slight inward deviation which is permitted by glasses of this strength is not noticeable, and is in no way harmful.

In the application of this method it is advisable to correct only a portion of the esophoria, a prismatic strength of one-half or two-thirds of the amount manifested at 6 metres being, in favorable cases, sufficient to relieve asthenopia, while total correction will not usually be tolerated. Prisms prescribed for the relief of esophoric asthenopia must ordinarly be worn constantly; occasionally in esophoria which is not attended by spasmodic action of the internal recti, the tendency to excessive convergence disappears in near vision, and in such cases it suffices to wear the prisms for distant use only.

In minor degrees of esophoria relief may be expected from the use of prismatic glasses; but, unfortunately, in many cases the excess of convergence is so great that only a small portion can be corrected within the limits prescribed for such glasses. In some cases, also, in which relief is at first afforded, the esophoria increases under the relaxing influence of the prisms, so that the strength of the latter has to be increased; and if the limit has already been reached, this method is no longer applicable.

Prescription of Prisms.—Eyes which require prisms require also, as a rule, lens-correction of ametropia. Any form of lens curvature may be ground upon the appropriate prismatic correction. It is apparent that a displacement (decentring) of the centre of a convex lens inward or of a concave lens outward has the effect of adding a prism, *base in*, to the lens, while decentring a convex lens outward or a concave lens inward has the effect of adding a prism, *base out*. Tables indicating the prismatic effect resulting from decentring may be obtained from opticians; but owing to the size of rough-ground lenses, it is not possible to decentre more than 1 cm., and, consequently, in lenses of low power only a weak prism-equivalent can be obtained.[1]

[1] The following rule (Prentice) is useful: a decentring of 1 cm. affords as many prism-dioptres as there are dioptres in the lens.

The oculist may, if he so desires, order the prism to be made by decentring, but it is more convenient for him to write for the required lens + the required prism, as $\begin{cases} \text{R. } +2 \text{ D. sph.} + 2^{\triangle}, \text{ base out.} \\ \text{L. } +3 \text{ D. sph.} + 2^{\triangle}, \text{ base out.} \end{cases}$ In this case the prismatic equivalent could be obtained by decentring the lenses outward, the 2 D. lens 1 cm. and the 3 D. lens 6 mm., and the optician would be justified in so filling the order. But here, as in all cases, the accuracy of the optician's work must be determined by the oculist, who should examine the glasses after they have been made.[1]

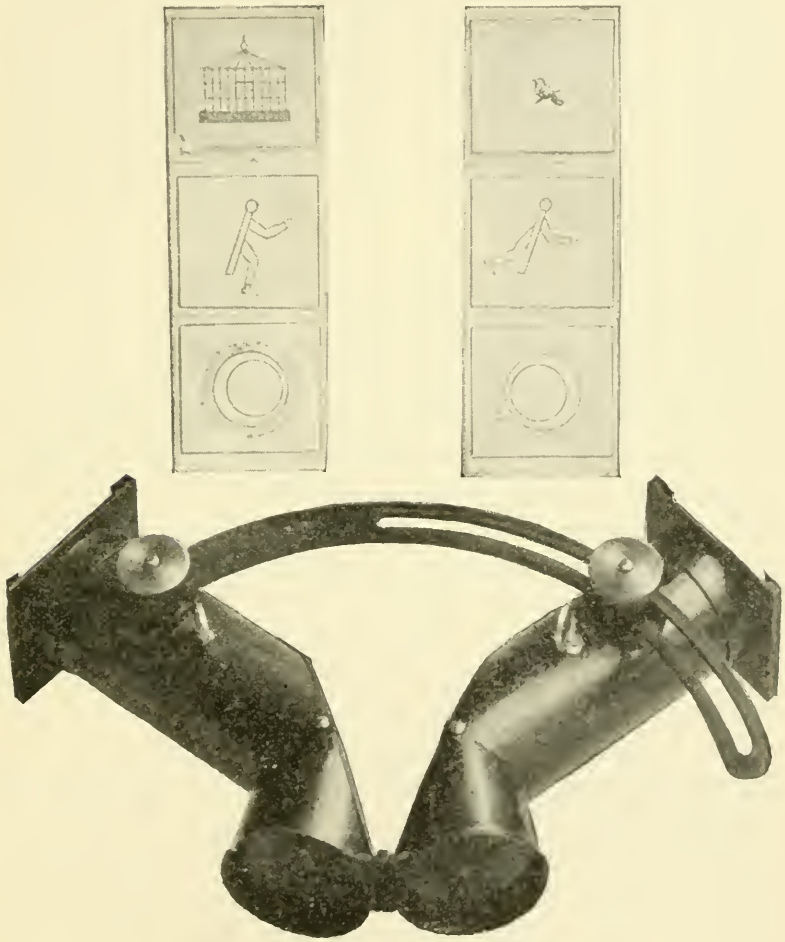
When the principal plane of the prism is to be placed horizontally or vertically, the simple designation *base in*, *base out*, *base up*, or *base down* suffices to denote the desired position; but when the principal plane (or the base-apex line) is to be placed in an oblique meridian, the angular markings on the trial frame are used. In using this notation it must be remembered that the base of the prism is at right angles to the principal or deviating plane; thus if we wish to place a prism so as to deviate light in the direction *A D* (Fig. 12) making an angle of 35 degrees with the horizontal line, its base must make an angle of 125 degrees with the horizontal or zero line.

Stereoscopic Exercises in Convergent Strabismus.—In a certain proportion of cases of convergent strabismus in children, in which the deviation is not overcome by correction of the ametropia, the failure is due to a deficiency in the impulse for binocular vision. In such cases success may attend the long-continued training of binocular perception. Javal and Landolt (by whose advocacy this method has received its deserved attention) and others have constructed spe-

[1] The strength of a prism may be determined from a prism-dioptre scale (p. 40), or by neutralizing the displacement with a prism taken from the trial case.

cially devised stereoscopes and pictures for the cultivation of binocular vision. Of all these instruments that of Claud Worth (the amblyoscope, Fig. 90) is the

FIG. 90.



Worth's amblyoscope.

most convenient, in that by its aid binocular vision is possible even when the eyes are affected with a high degree of strabismus. It is also possible to draw attention to the image as formed in the amblyopic

(undeveloped) eye by giving to this eye a more intense illumination than that which is given the better eye.[1]

In those cases in which it is not to be expected that stereoscopic training will overcome the strabismus, the prolonged daily use of such exercises with the amblyoscope is yet of very great value in preventing amblyopia ex anopsia and in developing the fusion sense while awaiting a suitable time for operative measures. The same exercises are likewise useful for developing the fusion sense and inciting binocular vision after operative measures have overcome the greater part of the strabismus.

Worth concludes, as the result of the examination of a large number of children, that binocular vision is first attempted about the sixth month of age, and that the development of the fusion faculty is completed by the end of the sixth year. In order, therefore, that stereoscopic exercises may be effective they must be begun at an early age, preferably before the fifth year. This constitutes the chief obstacle to this plan of treatment, since the very young children for whom it is applicable frequently fail to give the co-operation necessary for success. The experience of Worth, however, shows that much can be accomplished by the exercise of patience and care.

Use of Atropin and Bandaging in Developing the Amblyopic Eye.—In those cases in which stereoscopic exercises are not available, the amblyopic eye may be trained by bandaging the better eye for a brief period once or twice a day, thus necessitating fixation with the amblyopic eye. The use of atropin in the better eye

[1] This may be accomplished by placing an electric lamp in front of each opening, the lamp being placed nearer on the side corresponding to the weak eye (Worth). In the instrument made by Wall & Ochs the unequal illumination is produced by diaphragms, the openings in which carry smoked glasses of varying intensity.

Landolt equalizes the two impressions by blurring the image in the better eye with a strong convex lens.

is also of material assistance, since it compels the inferior eye to be used for near vision.

Prism Exercises.—Some ophthalmologists believe that the insufficiency of divergence which is present in esophoria may be overcome by prism exercises. The method of procedure consists in having the patient look at a distant candle flame alternately with and without divergent prisms (*bases in*), these being preferably placed in a spectacle frame and raised and lowered at intervals of five seconds (Savage[1]). By the rhythmical contractions thus produced in the external recti these muscles are said to be strengthened and thus to be enabled to overcome the excess of convergence. Even in the most favorable cases a prolonged course of such exercises is required to effect a cure; in fact, the predominating opinion among ophthalmologists is that relief from asthenopia is not often accomplished by this method.

Operative Treatment.—It is the custom of some surgeons to perform *partial tenotomies* even in slight esophoria, in preference to the prescription of prismatic glasses. The effect of a small incision in the tendon is very uncertain, and a number of operations must usually be performed before the desired result is obtained. The immediate effect of such an operation is a weakening of muscular action, but unless the section is extensive no retraction of the fibres takes place, and after union at the original point of attachment the full muscular power is regained. Because of this uncertainty it is better to reserve operative procedure for those cases in which less radical means have proved unsuccessful or are evidently insufficient. Esophoria exceeding 10° can rarely be successfully treated by prisms; in such cases (if all other means have failed to

[1] For a detailed description of this method consult Ophthalmic Myology (Savage), p. 135.

give relief) operation may be undertaken, provided the symptoms are of sufficient gravity to warrant this procedure.

The operative treatment of esophoria consists in a carefully guarded tenotomy of the internal rectus or an advancement of the external rectus; in either operation it is preferable to divide the effect between the two eyes in the higher degrees of esophoria. Of these two operations tenotomy is more frequently selected as being the simpler and less painful at the time of operation and during the healing process. The possibility, however, of a resulting deficiency of convergence, as sometimes occurs, leads many surgeons (notably Landolt) to believe it more rational to strengthen the weak external recti (by advancement) than to weaken the power of the internal recti. The surgeon may be aided in his choice of an operation by examination of the fields of fixation and of the power of convergence and divergence. When the esophoria is due to weakness of divergence, and not to overaction of convergence—that is, when convergence is not decidedly greater than the normal amplitude—advancement is the only permissible operation.

The operative treatment of convergent strabismus likewise consists in tenotomy of the internal rectus or advancement of the external rectus, the effect being preferably divided between the two eyes except in the lower grades of strabismus. When the operation is to be performed upon only one eye at the first sitting, the inferior (squinting) eye should always be selected.

It is especially in the extensive tenotomies undertaken for the cure of high convergent strabismus that subsequent deformity is liable to occur, such as sinking of the caruncle, proptosis, and even extreme divergence with marked limitation of movement. Hence, in all cases of convergent strabismus in which it is apparent that a moderate tenotomy (as hereafter described) on

each eye will not suffice, an advancement of the external rectus combined with the tenotomy must be undertaken, the effect being preferably divided between the two eyes. Here, also, some surgeons make advancement the primary operation, using tenotomy only in combination with advancement when the latter procedure alone is insufficient.

The proper age for operative intervention in convergent strabismus depends upon the probability of obtaining binocular vision. If the operation is to be undertaken solely for the cosmetic result, vision being hopelessly defective in the squinting eye, the procedure should be delayed until the eighth or ninth year, since in a small proportion of cases a spontaneous cure of spasmodic convergence occurs in early childhood. If, on the other hand, stereoscopic training with the amblyoscope evokes a strong desire for binocular fusion, an early operation is demanded (Worth), provided the non-operative methods aforementioned have proved unsuccessful.

Tenotomy.—The first operation for the cure of strabismus was undertaken by Dieffenbach (1839). Since he divided the body of the muscle, not the tendon at its insertion, disastrous results inevitably followed in the majority of cases, and consequently the procedure fell into disrepute. The method of Dieffenbach was improved by Jules Guérin and others, the introduction of the division of the tendon close to the sclera being due to Boehm (1845). The technique of the operation as recommended by Boehm was still further improved by von Graefe, Critchett, Snellen, and Arlt, each of whom has given us a method bearing his own name.

Von Graefe's open method consists in incising the conjunctiva over the tendon, exposing the latter to view, passing a squint-hook under the exposed tendon and dividing the latter between the hook and scleral insertion (Fig. 91).

Critchett's subconjunctival method is similar to the open method except that the tendon is not exposed, a small conjunctival incision being made at the lower border of the muscle, and the tendon divided subconjunctivally.

In *Snellen's method* the conjunctiva and tendon are buttonholed near the centre of the tendinous insertion, and the tendon detached subconjunctivally upward and downward. This method is particularly adapted for partial tenotomies and for all tenotomies undertaken for the relief of esophoria.

Arlt's method differs from the others in that he grasps the tendon with fixation forceps, using only a small squint-hook to discover any fibres which remain undivided by the first incision of the tendon.

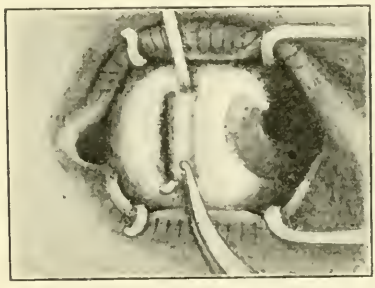
Tenotomy should be performed under the influence of a local anæsthetic (4 per cent. solution of cocain hydrochlorate or one of its substitutes) whenever possible; the employment of a general anæsthetic, which is necessary in certain cases of timidity, precludes the possibility of testing the muscular balance during the course of the operation. A solution of the suprarenal extract may be used to heighten the anæsthetic action of the cocain and to give a bloodless field of operation; but the resulting shrinking and rigidity of the tissues render the operation more difficult (Knapp). Here also, as in all surgical procedures, every possible precaution must be taken to prevent infection; the instruments and the dressings must be sterilized, and the surgeon's hands and the conjunctival sac and lids must be thoroughly cleansed.

The details of the operation vary with the individual preferences of the operator. The description here given will serve as a useful guide for the inexperienced surgeon.[1]

[1] Slightly modified from Casey Wood's description in Posey and Wright's Diseases of the Eye, Nose, Throat, and Ear.

The lids being held open by a speculum, a fold of conjunctiva and capsule over the central part of the insertion of the muscle is grasped with fixation forceps; the tissue so grasped is drawn slightly away from the globe and an incision made with the probe-pointed tenotomy scissors, care being taken not to cut through the tendon itself. By enlarging the opening thus made above and below, if necessary, space is given to enable the surgeon to pass a strabismus hook behind the exposed tendon so that its point presents at the border opposite to that of its insertion. If a partial tenotomy is to be done, a buttonhole snip

FIG. 91.



Tenotomy of the internal rectus (Graefe's method).

is made in the centre of the tendon; from this central opening the incision is extended toward each margin until the desired effect is obtained. The incision must be extended equally toward each margin so as to avoid disturbance of the meridional adjustment. A complete tenotomy may be done in the same way by extending the incision quite to the margins of the tendon, or the incision may be begun at one margin and extended to the other, the under blade of the scissors being made to follow the strabismus hook as a guide; the incision should be made between the hook and the attachment of the tendon (Fig. 91). If, on testing, the first result is deemed insufficient, the wound

in the capsule and conjunctiva is enlarged and the supplementary fibres on each side of the tendon are carefully and gradually divided on the hook, several deviation tests being meantime made. The effect of a simple tenotomy, when the retaining lateral fibres are undisturbed, varies between five and ten prism-dioptres. If the capsular attachments are undermined and divided, a greater effect follows, but at the risk of over-correction.[1]

After completion of the tenotomy the conjunctival wound may be sutured; some surgeons, however, consider this unnecessary. The after-treatment consists in the application of cold boric acid solution for the first eight or ten hours, followed by a simple collyrium.

If an over-correction is found within one or two days after operation, a suture, including the cut end of the muscle, Tenon's capsule, and the conjunctiva, should be so placed as to remedy the over-effect.

Bandaging is ordinarily unnecessary, and it is objectionable when binocular vision is expected to result, since the exercise of this function should be begun as soon as possible after the operation.[2]

Occasionally profuse bleeding occurs, either from anomalous blood supply or from cutting too deeply into the orbital tissues. In some such cases it may be necessary to postpone the operation.

Advancement.—Jules Guérin was the originator of the idea of advancing the tendinous insertion so that

[1] Knapp holds, as the result of a very large experience, that it is safe to overcome a deviation of 4 or 5 mm. by tenotomy of the internal rectus, provided the following conditions are fulfilled: (1) In adduction the medial margin of the cornea should readily reach the caruncle; (2) the near-point of binocular fixation should not be less than 5 cm.; (3) the eyeball should not protrude; and (4) some convergence should be left. Failure in any one of these respects is indicative that a secondary divergence is liable to occur, and steps should at once be taken to diminish the effect of the operation. (Norris and Oliver's System of Diseases of the Eye, vol. iii. p. 865.)

[2] Landolt, however, advises binocular bandaging, believing that the darkness and absence of incentive to convergence are beneficial.

it would become attached at a more anterior position on the sclera, thereby increasing the rotative power of the muscle. Guérin's method, as improved by von Graefe, is known as the thread operation.[1]

Since the thread operation was very unsatisfactory, it was soon abandoned in favor of Critchett's method of stitching the tendon forward (1862). Of the numerous advancement operations in vogue at the present day all have their foundation in one of two methods—the *simple advancement*, as recommended by Schweigger, Swanzy, and others, and the *tendino-capsular advancement* of Critchett.

The numerous modifications of what may be called simple advancement have in common the dissection of the tendon from the conjunctiva and capsule. In other respects such operations vary: (1) in the manner of applying the sutures; and (2) in the method of obtaining increased muscular action; whether by reseeting a portion of the tendon and stitching the two ends together, or by exseeting the scleral attachment of the tendon and drawing forward the free extremity so as to give it more favorable insertion; or by making a loop or tuck in the tendon and leaving the redundant tissue to be absorbed.

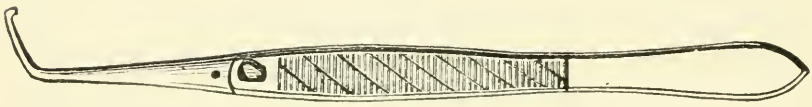
Advancement operations must usually be done under the influence of a general anæsthetic. The method of procedure recommended by Casey Wood may be described as follows:[2] A full curved needle is threaded with No. 3 iron-dyed silk, bringing the ends of the thread together and tying them in a hard knot, or both ends of the thread may be passed through the eye of the needle at the same time, leaving the end of the suture in the form of a loop instead of a knot. The needle is now passed through the conjunctiva and superficial

[1] A description of this procedure, with illustration, may be found in Ed. Meyer's Handbuch der Augenheilkunde, p 492.

[2] Slightly modified from Posey and Wright's Diseases of the Eye, Nose, Throat, and Ear.

layer of the sclera close to the cornea, as illustrated in Fig. 93. After the thread has been pulled about half-way, the needle is passed through between the threads on the other side of its entrance into the sclera, and then drawn taut, thus affording a firm point of fixation. A similar suture is fixed in the same manner upon the opposite side of the cornea. The conjunctiva and Tenon's capsule are now well divided over the muscle, the latter being thoroughly exposed and well cleaned of connective tissue. Two strabismus hooks are passed underneath the muscle (one from each side), or an advancement forceps (Fig. 92) is made to grasp the muscular body, so as to hold it steady and away from its bed. The sutures are now passed through the muscle from below upward as far back as is be-

FIG. 92.

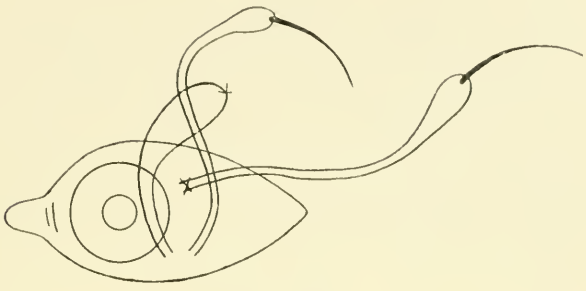


Prince's advancement forceps.

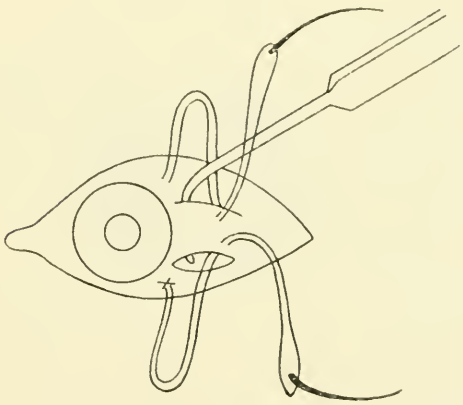
lieved necessary, and pulled about half-way. The muscle, still held with the hook or forceps, is now cut off just in front of the entrance of the sutures. The piece of tendon attached to the globe is grasped and cleanly dissected out. The sutures are now pulled taut, and both grasped between the thumb and finger, while the globe is fixed with forceps on the nasal side of the cornea and turned outward (in operating on the external rectus), while the muscle is advanced to the desired position. Care must be taken to preserve the proper lateral position, otherwise the meridional adjustment will be disturbed. The stitches are now tied in a surgeon's knot over the muscle, as illustrated in Fig. 93. The ends of the thread must be left long enough to protrude through the conjunctival wound

so as to facilitate removal of the sutures. Suturing of the conjunctival wound completes the operation. There may be some reaction following this operation, requir-

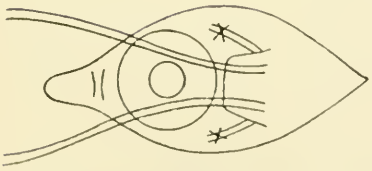
FIG. 93.



First step.



Second step.



Third step.

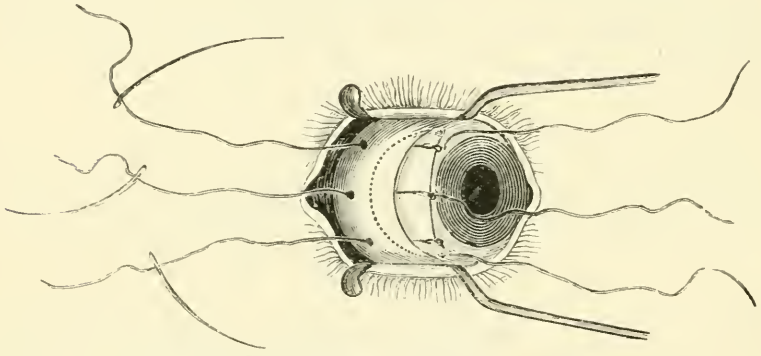
Final stage.

Introduction of sutures in advancement operations. (Black.)

ing the frequent application of hot fomentations, but with proper precautions this is unusual. The tendon sutures should be removed after the lapse of seven or eight days.

Although Critchett's operation for the advancement of the tendon with the conjunctiva and capsule is older than the simple advancement of Schweigger and others, the former operation continues to be the favorite method with many surgeons, and with only minor modifications. Briefly described, this operation consists in incising the conjunctiva and capsule over the insertion of the tendon to be advanced; dividing this tendon close to its insertion in the sclera, while the tendon and overlying structures are held with suitable forceps; introducing three or four sutures as

FIG. 94.



Critchett's advancement operation. (Juler.)

illustrated in Fig. 94; exsecting as much tendon and superadjacent tissue as is deemed necessary (the dotted outline in the figure); and finally tying the sutures, the degree of traction depending upon the effect desired.

Worth modifies this operation by including the upper and lower fourths of the tendon each in a loop of the thread, thus overcoming the tendency of the threads to pull away before union has occurred, and at the same time avoiding a post-operative atrophy of the fibres, which he believes is caused by the extensive ligation practised by Schweigger, Swanzy, and others

in simple advancement, and which Worth believes to be the cause of not infrequent relapses.[1]

Capsular advancement is the name given by de Wecker to an operation devised by him for advancing Tenon's capsule without inclusion of the tendon. It is only applicable in cases of very slight deviation.

In the performance of tenotomy and advancement the surgeon should always bear in mind that the effect of advancement diminishes, while that of a complete tenotomy increases for some time after operation. He should, therefore, aim to over-correct the strabismus in advancement; but in tenotomy a slight excess of convergence should be left.

DEFICIENCY OF CONVERGENCE.

Deficiency of convergence may be either latent or manifest, analogous, respectively, to latent and manifest excess of convergence. Latent deficiency is called *insufficiency of convergence* or *exophoria*, while manifest deficiency constitutes *divergent strabismus*.

As in excess of convergence, so in deficiency binocular vision may give place to strabismus with monocular vision only at certain times, as when the muscles are exhausted from prolonged use (*intermittent divergent strabismus*); if vision is equally good in the two eyes, either eye may be used for fixation while the other squints (*alternate divergent strabismus*); but if, as is usually the case, the vision of one eye is inferior to that of the other, the strabismus will be permanently confined to the inferior eye (*permanent divergent strabismus*). Furthermore, this kind of strabismus is comparable to non-paralytic convergent strabismus in that it is not a monocular affection, the conjugate movements being preserved (*concomitant divergent strabismus*).

[1] Lancet, May 11, 1901, p. 1323.

Etiology.—Myopia as a factor in the production of exophoria and divergent strabismus has been considered in Chapter XIII. It is apparent that myopia bears the same relation to deficiency as hyperopia does to excess of convergence: the weakness of the accommodative impulse, the elongation of the eyeballs, and the proximity of the farthest point of distinct vision all aid in rendering convergence difficult.

Aside from the myopic condition, non-paralytic deficiency of convergence may arise from overstrain of the eyes in near work, from innate preponderance of the external over the internal recti, from reduced physical vigor, and from mechanical impediment (as in exophthalmos).

Determining Causes of Divergent Strabismus.—The development of divergent strabismus from exophoria is favored by loss or deterioration of vision of one eye, and by so high a degree of myopia that the convergence required for binocular vision is impossible.

Divergent strabismus is ordinarily a condition of adult life; more rarely it develops in childhood, as in congenital myopia, or in high-grade hyperopia.

Symptoms.—Insufficiency of convergence (latent) gives rise to muscular asthenopia, especially when the eyes are tired from prolonged near work. The latter is sometimes impossible, so great is the disturbance produced by it. This disturbance is partly a symptom of over-taxation of the convergent muscles; but in the worst cases confused vision (crossed diplopia) from the impossibility of maintaining convergence is the chief factor.

The reasons assigned for the absence of diplopia in convergent strabismus are not applicable to divergent strabismus, which develops in adult life; but diplopia is not a common symptom in the latter condition either, because divergent strabismus usually develops only when the visual acuity of one eye is much re-

duced, so that exclusion of the false image is quickly learned. In those cases in which both eyes possess good visual acuity diplopia is a troublesome symptom in the developmental stage, but it subsequently disappears or ceases to give annoyance. Exclusion of the false image is aided by the position of extreme divergence, which is on this account frequently induced, for when the image falls upon the periphery of the retina, it does not excite attention so readily as when it falls near the macula.

Diagnosis.—The equilibrium tests which were described in considering the diagnosis of excess of convergence are equally applicable for the determination of deficiency of convergence. In latent deficiency binocular fixation is maintained during vision, but if one eye is covered it deviates outward, as is manifested by the movement of redress which is made at the moment of uncovering. In divergent strabismus the squinting eye (if capable of fixation) will move into position for fixation when the preferred eye is covered.

The red-glass test, Graefe's diplopia test, and the Maddox rod test, applied in accordance with previous instructions (p. 320), reveal crossed lateral displacement, the amount of divergence being measured by the prism, *base in*, which annuls this displacement.

The existence of exophoria, as thus determined, at 6 metres is strong evidence that the converging power is abnormally weak; but the converse does not follow, for insufficient convergence for near work is not incompatible with orthophoria, or even esophoria, in distant vision. The determining test consists in the direct measurement of the amplitude of convergence with the ophthalmodynamometer. The amplitude required depends upon the kind of work pursued, but an amount less than 8 ma. (corresponding to a near-point of 12.5 cm., or 5 inches) is insufficient for con-

tinuous reading or writing, since only about one-third of this amplitude is available for prolonged use.

It is here also, as in excess of convergence, of importance (especially in regard to operative treatment) to measure the diverging power by means of prisms; the strongest prism, base in, with which diplopia can be avoided is the measure of the divergence.

Measurements of the angle of strabismus and of the field of fixation may be made with the perimeter, as previously described. The inward rotations are usually considerably limited in old cases of divergent strabismus.

Treatment.—The importance of correcting any causative retractive error is apparent, and has been sufficiently considered in previous chapters. In addition, avoidance of overuse of the eyes in near work and other hygienic measures must be inculcated, according to the necessities of the case.

Prismatic glasses (bases in) are useful, within the limitations to which such glasses are restricted, for the relief of exophoric asthenopia. In those cases in which asthenopia arises only after prolonged near work, it suffices to wear the glasses for such work; but when there is marked exophoria at 6 metres, relief is usually afforded only by constant use of the glasses. The strength of prism which is most suitable for near work is somewhat uncertain, and it is well for the oculist to have on hand a supply of prisms in steel frames which may be furnished the patient for temporary use until the proper strength is determined. If the prisms are to be worn constantly, about one-half or two-thirds of the exophoria at 6 metres is the proportion most likely to prove satisfactory.

Prism Exercises.—Those who advocate prism exercises in the treatment of excess recommend it also, with greater confidence, in deficiency of convergence. The method of application is similar to that used

in excess of convergence, except that the bases of the prisms are reversed, being placed toward the temples.

Stereoscopic Training.—Owing to the circumstances under which divergent strabismus usually develops, training with the stereoscope is less frequently indicated than in convergent strabismus. Occasionally, however, when the impulse for binocular vision is lacking, while the visual acuity in each eye is good, stereoscopic exercises, either alone or in conjunction with surgical treatment, may prove useful.

Operative Treatment.—For the relief of asthenopia operative procedure should be undertaken only after all other measures have proved unsuccessful, and when it is reasonably certain that the patient's symptoms are due to insufficiency of convergence, and not to some other source of nerve irritation. Of the two operations —tenotomy of the external and advancement of the internal rectus—tenotomy is the simpler, and may be selected in suitable cases. There is less danger of disastrous result from a properly performed tenotomy of the external than of the internal rectus. Diplopia, occurring immediately after tenotomy of the external rectus is usually succeeded in a short time by single vision, if the operation has been done under proper indications. Tenotomy should never be selected unless the prism test shows the divergence to be decidedly in excess of the normal amount. For the relief of weakness of convergence without any excess of divergence advancement of the internal rectus is the only permissible operation; but before undertaking any operation it must be well established that the lack of convergence is not due to lesion of the convergence-centre (paralysis of convergence).

In strabismus of long standing simple tenotomy has but little effect in overcoming divergence. In such cases advancement (usually on both eyes) should be

combined with the tenotomy, and by this means divergent strabismus may usually be cured or much improved.

UNEQUAL VERTICAL ADJUSTMENT.

In high convergent strabismus there is almost always added an upward deviation of the squinting eye. Aside from this, non-paralytic vertical strabismus does not often occur, the tendency which sometimes exists for one eye to assume a higher level than that of the other more commonly remaining latent. This latency is called, according to Stevens' nomenclature, *hyperphoria*—right or left, according as the right or left eye tends to assume the higher position. Hyperphoria of 1°, or even less, is capable of giving rise to severe asthenopia.

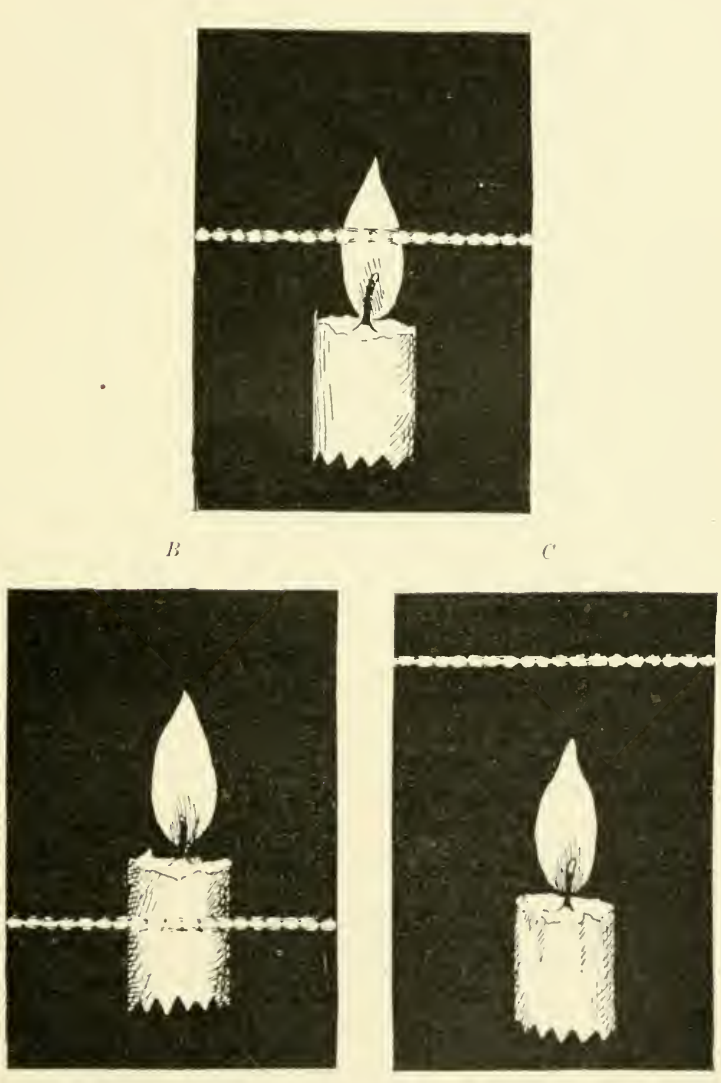
Etiology.—The only explanation that can be given for the occurrence of hyperphoria is that the balance of power between the elevator and the depressor muscles of one eye differs slightly from that of the other.

Diagnosis.—This is made by the production of horizontal diplopia (with a 10° prism, base in, or with the phorometer), or by the Maddox rod test. In the diplopia test if the two images are on the same level, there is no fault of vertical adjustment; if the image, as seen with one eye, is higher than that seen with the other eye, the eye which furnishes the lower image is the hyperphoric eye. The prism which causes the two images to be seen in the same horizontal plane is the measure of the hyperphoria, the base of the prism being down or up according as it is placed before the higher or the lower eye.

If the Maddox rod is used, the cylinder is placed vertically, and the eye before which it is placed will observe a horizontal streak of light (Fig. 95). If the vertical adjustment of the muscles is perfect, the streak

will pass through the flame as seen with the other eye; if the streak does not pass through the flame, the eye

FIG. 95.



Maddox rod test for vertical deviation; the rod is before the right eye. *A*. The line passes through the flame—orthophoria. *B*. The line passes below the flame—right hyperphoria. *C*. The line passes above the flame—left hyperphoria. (de Schweinitz and Randall.)

before which the rod is placed is higher or lower than the other eye, according as the streak is below or above the flame, and the prism which causes the streak to pass through the flame is the measure of the hyperphoria.

It is useful also to measure the power of right and left *sursumduction;* that is, the power of the right and left eye, respectively, to deviate relatively upward. The strongest prism, base down before the right eye or base up before the left eye, with which diplopia can be overcome, measures *right sursumduction;* similarly, the strongest prism, base down before the left eye or base up before the right eye, with which diplopia can be overcome, measures the *left sursumduction.* In normal balance sursumduction, right or left, is about 2 (Stevens). A higher degree of sursumduction for one eye than for the other indicates hyperphoria of the eye which has the greater sursumduction. In order to determine whether the relative hyperphoria is due to overaction of the elevator muscles of the higher eye or to underaction of the depressors of the lower eye, recourse must be had to measurement of the fields of fixation.

Uncomplicated vertical strabismus is determined by the tests which reveal hyperphoria, and in addition there is vertical diplopia without the aid of the horizontal prism.

Treatment.—Since hyperphoria does not reach a high degree of deviation, the asthenopia to which this imbalance gives rise may in favorable cases be overcome by the use of prismatic glasses. The strength of the glass should be divided between the two eyes, the base being placed down before the higher eye and *vice versa.* The same proportion of error (one-half or two-thirds) should be corrected as has been recommended for other forms of heterophoria.

The concurrence of slight hyperphoria with greater

lateral heterophoria does not indicate the necessity of correcting the vertical error; at least, until correction of the lateral imbalance has failed to give relief. On the other hand, as shown by Stevens, the hyperphoria is in some cases the primary defect, the lateral disturbance being produced by the muscular effort to overcome the vertical error. When it becomes necessary to correct both lateral and vertical heterophoria the equivalent prism and the position of its base can be determined in accordance with instructions given in Part I. (p. 40).

If prismatic treatment proves unsuccessful in hyperphoria or in vertical strabismus, tenotomy of the superior rectus of the higher eye or advancement of the inferior rectus is permissible, provided the symptoms are of sufficient gravity to justify operative interference. But here, again, the caution which has been given for other forms of heterophoria must be repeated. The existence of slight or even considerable deviation from orthophoria is by no means to be accepted as positive evidence that this deviation is the cause of the asthenopia or headache or other reflex disturbance of which the patient complains. If prisms do not afford a fair measure of relief in heterophoria, except in the highest degrees of lateral insufficiency, it may be reasonably assumed that operative treatment will be equally unsuccessful.

CYCLOPHORIA AND CYCLOTROPIA; ANAPHORIA, ANATROPIA, KATAPHORIA, AND KATATROPIA.

Cyclophoria and *cyclotropia* are the terms adopted by Savage to express, respectively, faulty tendency and faulty position of the antero-posterior meridians of the eye, which he believes to be an important factor in the etiology of asthenopia.

These disturbances, which are due to abnormal action of the oblique muscles, may be determined with the aid of a Maddox double prism (Fig. 43). If this is placed before one eye so that its double base line lies horizontally and bisects the pupil, while a horizontal black line on white paper is viewed through this eye, two horizontal lines will be seen; if the other eye is now opened, a third line will be seen between the other two lines. If the meridional adjustment of the eyes is perfect, this third line will be parallel to the other lines; if it is not so, there is cyclophoria or cyclotropia. The treatment employed by Savage in this disturbance consists in rhythmic exercise of the oblique muscles with cylindrical lenses.[1]

Anaphoria and *anatropia* are the terms adopted by Stevens to express, respectively, a tendency to upward deviation, and an actual upward deviation of both visual lines above the most favorable plane for passive adjustment; *kataphoria* and *katatropia* express the opposite conditions. Anatropia, characterized by deficient downward rotation, may give rise to asthenopia in persons whose work entails continual exercise of the depressor muscles, as is required in most kinds of near vision. A prism, base down, before each eye will relieve the strain in moderate cases; in more marked upward deviation tenotomy may be required (Stevens).

SPASMODIC CONJUGATE DEVIATION.

Spasmodic conjugate deviation sometimes occurs as a symptom of irritative cerebral lesion, being the opposite condition to paralytic conjugate deviation (p. 378).

[1] Savage, Ophthalmic Myology, p. 323.

NYSTAGMUS.

Nystagmus consists in a rapid, short, oscillatory motion of the eyes. The direction of motion may be lateral (*horizontal nystagmus*), vertical (*vertical nystagmus*), or there may be a rotatory motion around the antero-posterior axis (*rotatory nystagmus*). The last variety may be combined with horizontal or vertical motion (*mixed nystagmus*). Both eyes are affected except in rare instances. The nystagmus is more pronounced in some positions than in others, being worse in forced positions of the eyes.

Etiology.—Nystagmus is very common among coal miners, being due to the long-continued use of the eyes in forced rotation obliquely upward (*miners' nystagmus*).

This affection also occasionally develops in adult life as the result of cerebral lesion (disseminated sclerosis).

Aside from the aforementioned conditions, nystagmus almost always dates from early infancy; it occurs when the vision of both eyes is so highly defective that the impulse for macular fixation is not acquired. It does not occur in complete blindness; hence, it is apparent that the nystagmic movements are in some way associated with the effort to obtain better vision, the improvement of vision being derived from these movements in the same way, perhaps, that the peripheral field of vision is greater when the examiner moves the test object to and fro than when this object is held motionless.

Chief among the causes of such defective vision as results in nystagmus are the complications of ophthalmia neonatorum, albinism, congenital opacity of the cornea or lens, and, sometimes, very great refractive error.

Very rarely congenital nystagmus has been found to coexist with good visual acuity; in such cases the

movements must be attributed to some anomaly of the nerve centres.

Symptoms and Diagnosis.—In nystagmus which arises in infancy there are no subjective symptoms attributable to the oscillatory movements, but in that which develops in adult life the motion of the eyes makes all objects appear unsteady, with resulting confusion of vision, vertigo, and other disturbances.

The diagnosis of nystagmus is readily made from visual inspection. Clonic contractions of the ocular muscles occur physiologically when the attempt is made to hold the eyes in the position of maximum rotation. This condition should not be mistaken for nystagmus, which is present in all directions of the gaze.

Treatment.—Miners' nystagmus is cured by cessation from coal-getting. If possible, a permanent change of occupation should be made, since the disease is liable to return on renewal of work in the mines.

Treatment is evidently unavailing in nystagmus which results from incurable lesion of the brain or of the eyes. Even in those cases in which vision can be improved by iridectomy or other surgical procedure, the nystagmus is benefited only when the operation is performed at an early age.

DISORDERS OF MOTILITY CAUSED BY MECHANICAL IMPEDIMENT.

Limitation of ocular movement may be due to exophthalmos, orbital tumor, or allied condition. Such cases require no special consideration here, the disturbance of motility being of secondary importance in comparison with the etiological condition.

Loss of function is also produced by improperly performed tenotomy or by accidental section of a muscle back of Tenon's capsule.

CHAPTER XVIII.

PARALYTIC DISORDERS OF MOTILITY.

Paralytic disturbance of function may be due to lesion in any part of the course of the motor nerves, from their peripheral expansions to the highest centres presiding over muscular action. As regards the motor apparatus of the eye, such disorders may be conveniently divided into two classes. The first class includes paralysis arising from a lesion situated anywhere in the course of the nerve up to the nucleus (inclusively) which controls monocular muscular action; the second class embraces those rarer cases of paralysis of associated movement, due to lesion of the centres which preside over the working of the two eyes in unison, or to lesion of the centres or fibres which convey impulses to the motor centres.

PARALYSES OF THE OCULAR MUSCLES.

In this, the first class of paralytic disorders, the loss of muscular power is absolute; that is, it exists equally for all innervational impulses. The loss of power may be partial (paresis) or total (complete paralysis).

Paralysis may affect any one of the ocular muscles singly, or it may involve a group of muscles of one eye, or one or more of the muscles of each eye.

The external rectus and the superior oblique, each having its own independent nerve, are most frequently singly paralyzed; while the internal, superior, and inferior recti, and the inferior oblique, all being sup-

plied by the third nerve, are usually involved in a combined paralysis, although each of these muscles is sometimes singly paralyzed, only a portion of the third nerve being affected.

All the extrinsic muscles of the eye may be paralyzed, while the iris and ciliary muscle are unaffected, since the nucleus of these intrinsic muscles is anterior to that of the extrinsic muscles. Paralysis of this kind is called *external ophthalmoplegia* in contradistinction to *internal ophthalmoplegia*, which affects only the iritic and ciliary muscles (p. 308). Paralysis of both internal and external muscles constitutes *total ophthalmoplegia* .

Congenital paralysis may affect all the muscles of the eye, but it is usually confined to one external rectus, or to the two superior recti in conjunction with ptosis. In these cases the paralysis is associated with failure of muscular development, but the origin of the disease is probably nuclear.

A peculiar and rare form of congenital paralysis, the pathological nature of which is not well understood, consists in a loss of the power of abduction, associated with retraction of the eyeball and narrowing of the palpebral fissure in adduction.[1]

Ophthalmoplegic migraine (Charcot) is a form of recurrent paralysis attended by nausea and headache on the affected side. The disease attacks children and young adults. At the early stage of the disease the muscles regain their power in the interval between the attacks, which may last from a few days to several months, but later a permanent paresis results. The pathology of this affection is obscure. The third nerve is the seat of this kind of paralysis, only a few cases having been observed in which the sixth nerve was attacked.

[1] Evans, Ophthalmic Review, January, 1903, and Wolff, Alling, and Knapp, Archives of Ophthalmology, vol. xxix. pp. 297, 310, and 311.

Etiology.—Oculo-muscular paralysis may be due either to intra-cranial or to orbital lesion. Intra-cranial paralysis may be again divided, in accordance with the site of the lesion, into *nuclear*, *fascicular*, and *basilar*. The most common cause of the intra-cranial paralysis is syphilis, the gummatous deposit of which produces pressure upon the nerves or their nuclei. The principal other causes are non-syphilitic brain tumors, meningitis, aneurism, hemorrhage, tabes, disseminated sclerosis, and certain diseases which are especially liable to cause injury to nerve tissue, as diabetes (probably hemorrhagic), and poisoning by alcohol, tobacco, and lead.

Orbital paralysis may result from diphtheria, rheumatism, diabetes, or lead poisoning (each of which may give rise to neuritis), from orbital tumor, hemorrhage, fracture or exostosis in the region of the optic foramen, etc.

Symptoms.—There are six important *general symptoms* of oculo-muscular paralysis, namely, limitation of movement, strabismus, diplopia, false projection, vertigo and unsteadiness of gait, and oblique position of the head. These general symptoms are common to all paralyses.

Limitation of Movement.—The rotative power of the eye is always abnormally circumscribed in the field of action of the paralyzed muscle. In complete paralysis this limitation is readily determined by directing the patient to follow with his eyes (his head being unmoved) the point of a pencil or other object moved in various directions before the eyes, when the examiner will notice that the paralyzed eye fails to follow the other in certain movements. In incomplete paralysis (paresis) the limitation of movement is often too slight to be thus determined; this is especially the case in affection of the oblique muscles. In such cases assistance may be gained from the measurement of the

field of fixation with the perimeter or with the tropometer.

Paralytic Strabismus.—This differs from concomitant strabismus in that the latter is maintained in all directions of the gaze, while the former is manifested only when the object of vision lies within the field of action of the paralyzed muscle. Thus, in paralysis of the left external rectus the right eye will properly fix an object situated on the left side, but the left eye cannot be turned in this direction; consequently there will result a convergent strabismus of the left eye. When, however, the gaze is directed straight forward the strabismus becomes less marked, or in paresis it may vanish, giving place to binocular fixation, as it will also do in complete paralysis when the object is moved to the extreme right.

Between paralytic and concomitant strabismus there is also another point of difference which is of great diagnostic importance : in concomitant strabismus the angular deviation of the non-fixing eye is the same whether one or the other eye is used for fixation; but in paralytic strabismus the deviation of the paralyzed eye (*primary deviation*) when the sound eye is fixing is less than the deviation of the sound eye (*secondary deviation*) when the paralyzed eye performs fixation.

The explanation of the greater secondary than primary deviation in paralysis is to be found in the binocular innervation of the associated muscles involved in fixation. Owing to the diminution of power of the paralyzed muscle, a very strong impulse is required to enable the affected eye to move into position for fixation—as great an impulse as would be required in a state of health to effect extreme rotation; hence, this strong impulse being equally conveyed to the associated sound muscles of the other eye, these muscles are powerfully contracted, thus producing the great secondary deviation.

Diplopia.—This is the most prominent subjective symptom of paralysis developing in the muscle of an eye whose visual acuity is good. The diplopia occurs coincidently with the strabismus; that is, it is manifested whenever the gaze is directed toward the field of action of the paralyzed muscle. The patient may himself be aware of the existence of diplopia, or he may complain only of confused vision.

The analysis of diplopia is of the greatest diagnostic importance, for it is from the relative position of the true and the false image and from the direction of the gaze in which diplopia occurs that the seat of paralysis is most readily determined in those cases in which the limitation of movement is too slight to be apparent.

False Projection.—We have learned in the study of concomitant strabismus that the false image is improperly projected, giving rise to homonymous or crossed diplopia, according as the strabismus is convergent or divergent. The same error is made in paralytic strabismus; but in addition there is another kind of false projection which occurs when the paralyzed eye is performing fixation, the sound eye being covered. This false projection is due to the *muscular sense*, which enters largely into the judgment as to the position of an object relatively to the body. We know that a strong impulse is required in order to perform fixation of an object situated to the extreme right (for instance). If the right external rectus is paralyzed, it will require just as great an impulse for the right eye to fix an object situated slightly to the right as would be required to effect extreme rotation to the right in a healthy eye. Hence, if the subject of such paralysis, having his sound eye covered, is directed to look at an object situated on his right and then to point quickly with his finger toward the object, he will point too far to the right, because of the great innervation necessary to produce the requisite action of the paralyzed exter-

nal rectus; but in a moment, when he sees his finger pointing in the wrong direction, he will rectify his error. This is called *von Graefe's touch test.*

Vertigo and Unsteadiness of Gait.—These disturbances are the direct result of the diplopia and false projection. They disappear upon closure of the paralyzed eye.

Oblique Position of the Head.—This characteristic symptom results from the endeavor to avoid diplopia by turning the head toward the field of action of the paralyzed muscle, the rotation of the head thus supplanting that of the eyes.

Old Paralysis.—The foregoing symptoms become less characteristic the longer the paralysis has existed. The strabismus usually increases from contraction of the antagonistic muscles, and thus, existing to some extent throughout the field of fixation, simulates concomitant strabismus. Diplopia ceases to give annoyance or even disappears entirely from the acquirement of the habit of exclusion. False projection also disappears, since the person learns that an exaggerated impulse corresponds to only a moderate movement. With the disappearance of diplopia and false projection vertigo also vanishes.

Paralysis of the External Rectus (Sixth Nerve).—The *special symptoms* which characterize this paralysis are inability to rotate the eye outward (abduction), convergent strabismus, homonymous diplopia (Fig. 96), and rotation of the head toward the paralyzed side, and false projection toward this side. These symptoms are most pronounced when the object of vision lies on the side corresponding to the affected side, and they vanish when the object is moved to the extreme opposite side.

Paralysis of the Internal Rectus.—The characteristics of this paralysis are limitation of internal rotation (adduction), divergent strabismus, crossed diplopia

RELATIVE POSITION OF THE IMAGES IN PARALYSES OF THE OCULAR MUSCLES

(The false image is represented by dotted outline.)

Paralysis of left eye.

FIG. 96.

Paralysis of external rectus.

Lateral separation of images increases in looking toward the paralyzed side.

Paralysis of right eye.

Paralysis of left eye.

FIG. 97.

Paralysis of internal rectus.

Lateral separation of images increases in looking toward the sound side.

Paralysis of right eye.

Paralysis of left eye.

FIG. 98.

Paralysis of superior rectus.

Vertical separation increases in elevation and abduction. Lateral separation diminishes in abduction. Obliquity increases in adduction.

Paralysis of right eye.

Paralysis of left eye.

FIG. 99.

Paralysis of inferior rectus.

Vertical separation increases in depression and abduction. Lateral separation diminishes in abduction. Obliquity increases in adduction.

Paralysis of right eye.

Paralysis of left eye.

FIG. 100.

Paralysis of inferior oblique.

Vertical separation increases in elevation and adduction. Lateral separation diminishes in adduction. Obliquity increases in abduction.

Paralysis of right eye.

Paralysis of left eye.

FIG. 101.

Paralysis of superior oblique

Vertical separation increases in depression and adduction. Lateral separation diminishes in adduction. Obliquity increases in abduction.

Paralysis of right eye.

(Fig. 97), turning of the head toward the sound side, and false projection toward this side. The symptoms are most pronounced when the object of vision lies on the side corresponding to the sound eye, and they vanish when the object is moved to the extreme opposite side.

Paralysis of the Superior Rectus.—The external and internal recti rotate the eyeball around a single (vertical) axis when the object of vision is on a level with the eyes, and consequently the resulting homonymous or crossed diplopia is simple; that is, the two images are on the same level and parallel. But the action of all the other ocular muscles is more complex, as referred to the three primary axes, and paralysis of these muscles is attended by a more complicated relation between the true and false image than follows paralysis of the external or internal rectus. The superior rectus turns the eye directly upward only when the eye is simultaneously abducted to such a degree (about 23 degrees) that the antero-posterior diameter lies in a straight line with the line of action of the muscle; when the gaze is directed straight forward, the action of the muscle is divided between elevation, adduction, and rotation of the cornea about the antero-posterior axis, and the last-named action increases at the expense of the others as the adduction is increased. Hence, it is only in the first-mentioned position that paralysis of the superior rectus is accompanied by simple vertical diplopia; in other directions of the gaze the false image is displaced both vertically and laterally, and is obliquely inclined to the true image because of the rotation of the meridians of the eye.

In paralysis the displacement of the false image always corresponds to the direction of normal action of the paralyzed muscle, for the paralysis is followed by a displacement of the eyeball opposite to that of the normal muscular action, and we know that the

false image is displaced in a direction opposite to the displacement of the eye (p. 318). Since, therefore, the superior rectus turns the eye upward and inward and rotates the upper end of the vertical meridian inward, the false image must occupy the position represented in Fig. 98; that is, the diplopia is crossed, and the false image is above the true image, the lower extremity of the former being inclined toward the latter. Furthermore, it follows from the action of this muscle that the lateral separation of the images diminishes in abduction, that the obliquity is least in abduction and greatest in adduction, and that the vertical separation is greatest in looking upward.

Of the other symptoms, limitation of movement upward and inward, downward strabismus, and false projection require no special mention. The head is usually inclined backward and toward the shoulder of the healthy side.

Paralysis of the Inferior Rectus.—What has been said of the superior applies equally to the inferior rectus, with the modification that the inferior rectus draws the eye downward and inward and rotates the upper end of the vertical meridian outward; hence, in looking forward and downward there is slightly crossed diplopia, the false image being below the true image, and having its upper end inclined toward the true image (Fig. 99). The vertical separation diminishes on looking upward, the lateral separation diminishes in abduction, and the obliquity is least in abduction and greatest in adduction.

The limitation of movement is downward and inward, the strabismus upward and outward, and the inclination of the head downward and toward the shoulder of the paralyzed side.

Paralysis of the Inferior Oblique.—The inferior oblique turns the eye upward and outward and inclines the upper end of the vertical meridian outward; hence,

the false image is displaced upward and outward (that is, homonymously), and its upper extremity is inclined away from the true image (Fig. 100). The vertical separation of images increases when the patient looks upward and toward the sound side (adduction); the obliquity increases when he looks toward the paralyzed side (abduction); the lateral separation diminishes in adduction.

The limitation of movement is upward and outward, the strabismus is slightly downward and inward, and the rotation of the head upward and toward the paralyzed side, and inclined to the shoulder of this side.

Paralysis of the Superior Oblique. — The superior oblique turns the eye downward and outward and rotates the upper end of the vertical meridian inward; hence, the false image is displaced downward and outward (homonymously), and its upper extremity is inclined toward the true image (Fig. 101). The vertical separation of images increases in looking downward and toward the sound side (adduction); the obliquity increases in looking toward the paralyzed side (abduction); the lateral separation diminishes in adduction.

There is slight limitation of movement downward and outward, with a corresponding strabismus upward and inward. The rotation of the face is downward and toward the paralyzed side, with the head inclined toward the shoulder of the sound side.

Paralysis of the Third Nerve.—Paralysis, either complete or partial, of all the muscles supplied by the third or oculomotor nerve is more common than paralysis limited to one of these muscles. In complete paralysis the appearance is unmistakable: the eye, being subjected to the unopposed action of the external rectus and the superior oblique, is deviated outward and downward, the upper lid droops over the eye (ptosis), there is mydriasis and cycloplegia (if the intrinsic muscles are involved), and not infrequently

proptosis is present, because of the relaxation of the recti muscles which normally draw the eyeball into the orbit.

Since the eye is drawn outward and slightly downward, having the upper end of its vertical meridian inclined inward, the false image must be displaced inward (crossed diplopia) and upward, while its upper extremity is inclined toward the true image.

The effect of varying the direction of the gaze requires no special consideration, in view of what has already been said in regard to paralysis of the individual muscles. The head is turned toward the sound side, and is inclined toward the shoulder of the paralyzed side; the head is also thrown back in order to supplant the deficient downward rotation, and to compensate for the inability to raise the upper lid.

In incomplete paralysis ptosis may not be present, and the other symptoms (including the diplopia) are modified in accordance with the extent to which the various muscles are affected.

Combined Paralyses of the Ocular Muscles.—Several or all of the motor nerves of the eye may be simultaneously paralyzed, either from peripheral or nuclear lesion. Thus a nuclear paralysis of the third nerve is not infrequently associated with paresis of the fourth and sixth nerves, as is manifested by deficient action of the superior oblique and external rectus in conjunction with third nerve paralysis. By a further extension of the disease-process the paresis of these two nerves may develop into complete paralysis, thus causing absolute immobility of the eyeball. Similarly, the adjoining nuclei of the nerves of the other eye may be attacked, with resulting paresis or paralysis of some or all of the muscles of this eye.

Diagnosis.—The existence of paralysis of an ocular muscle is suspected when a patient complains of confused vision, vertigo, and uncertainty of gait, and

when in addition it is noticed that he does not direct his gaze straight forward, but turns his head toward one side, inclining it, perhaps, at the same time toward one shoulder. In such a case the suspected diagnosis is confirmed if direct inspection reveals limitation of movement and strabismus, the latter appearing or disappearing according as the gaze is directed toward or away from the field of action of the affected muscle.[1]

But in the more common condition of paresis of one or more muscles the limitation of movement cannot usually be determined by simple inspection. The appearance of slight strabismus is also liable to be deceptive, for apparent strabismus is not infrequently coexistent with binocular single vision.

If the strabismus is only apparent, binocular fixation may be demonstrated by the cover test and by the other methods enumerated in the preceding chapter. If real strabismus is revealed by these tests, paralytic is distinguished from concomitant strabismus in accordance with the characteristics of each, as previously mentioned; but in the exact diagnosis of the degree and seat of paralysis the study of the field of fixation and of the diplopia are the two essential matters.

Measurement of the Field of Fixation.—This is useful not only for the assistance rendered in making a diagnosis, but also for the record which it affords as to the degree of paralysis, thus enabling the physician to know whether the affection is improving under treatment. The field of fixation is determined with the tropometer or perimeter, as previously described.

Analysis of Diplopia.—The existence of diplopia is demonstrated by directing the patient to look at a candle-light or other suitable illumination, placed at a distance of 3 metres (10 feet) or more. The examina-

[1] Loss of movement due to section of a muscle (p. 358) may be excluded by the history of the case.

tion should be conducted in a darkened room, and preferably against a black background. If diplopia is present, two lights will be seen ; the image which is well defined (provided the visual acuity of the non-paralyzed eye is good) and correctly projected is the true image, while the indistinct and incorrectly localized light is the false image. By covering first one and then the other eye we determine which eye furnishes each image; or a red glass may be placed before one eye, thus coloring the light as seen with this eye.

After the existence of diplopia has been determined, the field of single vision and the field of diplopia are ascertained by moving the light in various directions, while the patient follows it with his eyes, his head remaining unmoved ; or, preferably (as recommended by Landolt), the light is stationary, while the patient's head is rotated in the various directions.

In making the diagnosis of the seat of paralysis the main points to be noted are: (1) Whether the false image is seen with the right or with the left eye ; (2) whether the diplopia is homonymous or crossed ; (3) whether the two images are parallel or obliquely inclined, and, if inclined, the relative direction of the false image; (4) whether the two images are on a level or one higher than the other ; in the latter case, whether the true or the false image is the higher; and (5) the effect of varying the direction of the gaze upon the lateral and vertical displacements and upon the obliquity. By careful study of these features in connection with the study of the physiological action of the ocular muscles and of the result of their paralysis, as delineated in the foregoing diagrams (p. 365), a proper diagnosis may usually be reached. Simple as this procedure may seem, the diagnosis of oculomuscular paralysis is in many cases a very difficult task. This is because the test on which we must mainly rely (diplopia) is subjective, and even intelli-

gent persons are very liable to error in describing these unfamiliar visual sensations; in the examination of ignorant or unobserving patients it is at times well-nigh impossible to gain intelligible answers. The most difficult cases are those of old paralysis and of paralysis complicated with defective visual acuity. In old paralysis and that in which the acuity of the paralyzed eye is defective, diplopia is with difficulty evoked and the direction of projection is uncertain; in paralysis complicated with defective acuity of the non-paralyzed eye it is hard to distinguish between the true and the false image.

Measurement of the Degree of Strabismus.—If the separation between the diplopic images is not too great, fusion may be effected by interposing a prism before one eye. When the prism is placed before the paralyzed eye the position of its base must correspond with the direction of displacement of the false image; when the prism is placed before the sound eye its base must be in the opposite direction. It is impossible to rectify the obliquity of the false image with a prism, but when the two images are otherwise brought together the obliquity is overcome either by rotation of the head or with the aid of the sound eye, thus allowing complete fusion of images. The strength of prism required for fusion measures the paralysis, each prism-dioptre representing one-half of a degree of strabismus. For the purpose of record the measurements should always be made with the object of vision in the same direction.

When the strabismus is too great for prismatic measurement, the perimeter may be used, just as in the measurement of concomitant strabismus.

Still another method consists in measuring, on an opposite wall, the linear distance between the two images; the distance of the patient from this wall being known, the angle of strabismus may be deduced.

Determination of the Site of the Lesion Productive of Paralysis.—The site of a lesion which produces paralysis is to be conjectured partly from the apparent etiology and partly from the accompanying symptoms.

Thus paralysis resulting from rheumatism, diabetes, lead-poisoning, or diphtheria is usually peripheral (*orbital*), although all except the first of these diseases is known to be capable of producing also nuclear paralysis. Orbital paralysis may also be diagnosticated when there are definite symptoms pointing to orbital fracture, hemorrhage, inflammation, or tumor.

Similarly, in paralysis complicating meningitis a *basilar* lesion would be suspected. Basilar paralysis may also be caused by hemorrhage, tumor, or aneurism compressing the ocular nerves in this part of their course. A basilar lesion would be especially indicated by symptoms of involvement of the whole group of adjacent nerves of one side, including the olfactory, optic, and the trigeminal, in addition to the motor nerves of the eyeball.

A *fascicular* lesion is determinable only in crossed paralysis; that is, when the paralysis affects the third or sixth nerve of one eye with simultaneous hemiplegia of the opposite side. The lesion (hemorrhage or tumor) must in this case lie in the pyramidal tract (or adjacent to it), so as to injure the fibres of the ocular nerve after they have left their nucleus, and at the same time to injure the fibres of the tract, which cross to the opposite side below this point. The lesion would be near the upper or lower border of the pons, according as the third or the sixth nerve were involved. The seventh (facial) nerve may be involved in conjunction with the sixth.

A *nuclear* lesion can be positively diagnosticated in paralysis of the third nerve without involvement of the internal branches. A peripheral lesion would not exclude the fibres which supply the intrinsic muscles,

but owing to the fact that the nucleus for the latter fibres is anterior to the nucleus for the rest of the nerve, a nuclear lesion may not implicate the internal branch.

It does not follow, however, that involvement of both external and internal muscles is necessarily due to peripheral disease, for a morbid process affecting the gray matter on the floor of the fourth ventricle may evidently attack both nuclei of the third nerve; it may also attack the other nuclei, thus causing paralysis of all the muscles of the eye.

Treatment.—Diphtheritic paralysis usually undergoes a spontaneous cure, which, however, should be assisted by tonic and hygienic measures.

Rheumatic paralysis also affords, as a rule, a favorable prognosis. The treatment consists in a suitable regulation of the diet, alkaline waters, and the administration of salicylates. This paralysis is liable to recurrence and sometimes proves incurable.

Diabetic paralysis is favorably influenced and sometimes cured by proper regulation of the diet. In lead-paralysis a more healthful occupation should be sought, and absorptives (iodides) should be administered.

In orbital paralysis resulting from fracture, cellular inflammation, exostosis, tumor, or other affection, the prognosis varies in accordance with the extent of injury inflicted upon the nerve tissue. The treatment consists in removing the causal lesion, so far as this may be possible.

Paralysis which is due to the various forms of poisoning (by alcohol, tobacco, etc.) affords a favorable prognosis, provided the deleterious substance is eliminated and its further access prevented before destruction of the nerve tissue ensues.

Syphilitic paralysis is usually amenable, if treatment is undertaken in good season; but occasionally this form of paralysis resists the most energetic treat-

ment, destruction of tissue taking place before absorption of the pathological deposit can be effected.

Tabetic paralysis not infrequently disappears with the advance of the systemic disease; but, in general, paralyses resulting from incurable brain affections present an unfavorable prognosis, treatment being from the nature of the case unavailing.

Even in the most favorable cases paralysis is essentially a chronic affection; several weeks must elapse —more frequently two or more months—before a cure can be effected. There are two remedies which are commonly used as routine practice in all ocular paralyses. These are strychnine (in full doses) and electricity. Electricity is usually applied on alternate days for a period of from five to ten minutes. If the galvanic current is used the strength should not exceed 3 or 4 milliampères, the positive pole being placed over the closed lids, the negative at the back of the neck.

The faradic current is also frequently applied, but with the electrodes placed on the skin of the neck (occiput) and lids it is certain that the electric current does not pass through the ocular muscles. On this account the plan has been advocated of placing one electrode on the conjunctiva as nearly as possible over the affected region. The same method may also be used in the application of the galvanic current. Local anæsthesia of the conjunctiva must previously be effected in order that this method may be tolerable.

Prismatic Glasses.—In slight paresis, the separation of the images not being great, the diplopia may be avoided by the use of prisms. Although the degree of paralytic strabismus varies with the direction of the gaze, so that it is not possible to order a prism which will prove satisfactory throughout the field of fixation, yet much comfort is derived from a prism which relieves the diplopia in the most common position of the

eyes—forward and slightly downward. In paresis of one of the depressor muscles, the superior oblique or the inferior rectus, it may suffice to annul the vertical displacement by a prism with its base down. Unless the prism is very weak its strength should be divided between the two eyes, the base of the prism before the sound eye being placed upward. If both vertical and lateral displacements must be corrected, the base of the prism must have an intermediate direction; or the vertical error may be corrected by one prism, its base being up or down, while the lateral error is overcome by the prism before the other eye, its base being in or out, according to necessity.

It is not necessary to overcome the entire strabismus by the prismatic action; when a certain degree of assistance is rendered the paretic muscle, the latter is enabled to exert its remaining power and thus to produce fusion of images. On this account prisms are very useful in paresis, since the muscles are stimulated by exercise, and contraction of the antagonistic muscles is prevented. The strength of the prismatic correction should be reduced as the paresis diminishes.

Prismatic and Stereoscopic Exercises.—Exercises with prisms or with the stereoscope are also advocated in paresis, and may be found useful in some cases. The methods are the same as are applied in concomitant affections.

Occlusion of the Paralyzed Eye.—In all cases in which the diplopia cannot be overcome by prisms suitable for wearing as spectacles, it is advisable to cover the affected eye with an opaque disk, so as to avoid diplopia and the disturbances to which it gives rise.

Muscle Stretching.—This consists in grasping the eyeball with forceps and rotating it forcibly a few times in the direction of action of the paralyzed muscle. This method, applied for one or two minutes every day, seems to exert a beneficial effect in some cases,

chiefly perhaps by preventing contraction of the antagonistic muscles. It is not advisable in recent paralysis. A local anæsthetic must be employed to prevent pain.

Operative Treatment.—This is permissible only in old paralysis in which there is decided contraction of the principal opposing muscle and in which there is no hope of curing the paralysis. The frequency of indication for such treatment is diminished by the fact that in long-continued paralysis annoying subjective disturbances are usually absent. In those cases in which operation is apparently indicated the result is frequently disappointing; the most that can be expected is improvement of the strabismus and relief from diplopia in the more common directions of the eyes. Operation can be of no benefit unless there is some power left in the affected muscle. Advancement of the muscle may increase this power, but if the antagonistic contraction is very great, tenotomy of the latter muscle must be combined with the advancement of the paralyzed muscle. In paralysis of the superior oblique as well as in that of the inferior rectus advancement of the latter muscle is the operation to be selected.

PARALYSES OF ASSOCIATED MOVEMENTS.

A lesion situated above the nerve-nucleus cannot produce a monocular disturbance of motility. Any limitation of movement produced by a lesion so situated must be binocular. This may consist in inability to turn the two eyes consensually to the right or to the left, or upward or downward; or all these motions may be normally performed, showing that there is no paralysis of any individual muscle, and yet the power of simultaneously contracting the two internal recti for convergence may be totally lacking.

Conjugate lateral deviation of both eyes to the right or left not infrequently occurs as a transitory symptom in cerebral hemorrhage (apoplexy). The cortical centre for rotation of the two eyes to the right lies in the left hemisphere; hence a destructive lesion in the left hemisphere causes loss of power of deviation to the right, with consequent deviation of the eyes to the left; that is, *the eyes look toward the lesion*. This is just the opposite to what occurs in irritative lesions, such as give rise to epileptiform convulsions. The spasmodic deviation produced by an irritative lesion may at any time be replaced by paralysis, if the lesion is of sufficient magnitude to produce destruction of tissue.

Conjugate deviation occurring in apoplectic attacks is a *distant* symptom—that is, the centres of ocular motion are not injured—the deviation probably results from suspension of function in the entire hemisphere (Swanzy[1]); there being no stimulation of the affected side, the opposing muscles draw the eyes in the opposite direction. The function of the affected hemisphere may be restored, or if permanently injured the other hemisphere, through intimate association, comes to the rescue, and the deviation is overcome.

Although conjugate lateral deviation is known to result from a lesion situated in the cortex or in the optic radiations, it cannot be said that all associated paralyses are due to lesions in this region. We do not know the situation of the lowest centres or nuclei which preside over binocular action; although it appears from the result of autopsies that in the case of lateral movements a portion of the nucleus of the sixth nerve exercises this control, since fibres from this nucleus pass to the opposite internal rectus as well as to the external rectus of its own side. Thus it would seem

[1] Norris and Oliver's System of Diseases of the Eye, vol. iv. p. 585.

that the nucleus of the sixth nerve on either side controls lateral movement to the corresponding side. Hence destruction of the nucleus at the point of origin of these two sets of fibres causes conjugate lateral paralysis. This symptom—conjugate lateral paralysis—is also sometimes produced by pressure upon the nerves by a lesion in the pons. In all these cases the deviation is opposite to that which occurs in cortical lesions; that is, the eyes look away from the lesion.

Paralysis of upward or downward movements of both eyes generally results from pressure by a tumor in the quadrigeminal region.[1]

Paralysis of Convergence.—This may be complete or partial; in the latter case it resembles non-paralytic insufficiency of convergence, and in some cases a distinction may be impossible.

Complete paralysis of convergence consists in a total abolition of the converging power without loss, as a rule, of power in any of the individual muscles, although the latter may be implicated by extension of the morbid process. Accommodation, on the other hand, usually participates in the paralysis, but without mydriasis. The eyes assume a position of parallelism or slight divergence, maintaining this position in near vision with resulting crossed diplopia.

The nucleus for convergence probably lies in the aqueduct of Sylvius, near the nuclei for the ciliary muscles; hence in paralysis of convergence a lesion in this region is presupposed, as it is unlikely that a cortical lesion would produce this paralysis without giving rise to other and more grave symptoms.

In the etiology of paralysis of convergence tabes holds the first place, this being the cause in the majority of cases which have been observed. Of the remaining causes, syphilis and poisoning by alcohol

[1] Swanzy, loc. citat., p. 598.

and tobacco are the most prominent. The insufficiency or weakness of convergence which occurs in neurasthenia may be appropriately regarded as a paralytic affection, since it is due to loss of power in the centres controlling this function.

Paralysis of Divergence.—This sometimes occurs in conjunction with paralysis of convergence, as manifested by homonymous diplopia in distant vision (or with a very weak prism, base in), together with crossed diplopia in near vision. Paralysis of divergence may also occur without paralysis of convergence, the etiology being the same as in the latter affection. Paresis of divergence, with consequent esophoria or esotropia, sometimes occurs in neurasthenia, constituting a troublesome symptom of that condition.

Treatment of Paralysis of Associated Movements.—This is such as is appropriate for the causal lesion, so far as that admits of cure. In paresis of convergence or of divergence the enfeebled action may be assisted by the use of prismatic glasses within the limits to which such glasses are subject.

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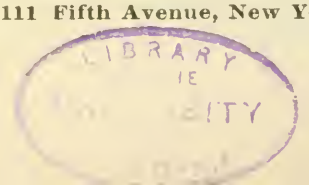

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